TM No. 931059

REFERENCE COPY

NAVAL UNDERSEA WARFARE CENTER DETACHMENT
NEW LONDON, CT

Technical Memorandum:

EVALUATION OF WATER AND AIR GUN SEISMIC SOURCES AT SENECA LAKE

Date: 14 May 1993

Prepared By: Mark J. Vaccaro
Code 3112
Environmental Acoustics Branch

Richard M. Noble
Code 3321
Towed Array and Ocean
Engineering Branch

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
14 MAY 1993	**Technical Memo**	**14-05-1993 to 14-05-1993**

4. TITLE AND SUBTITLE
Evaluation of Water and Air Gun Seismic Souces at Seneca Lake

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Mark Vaccaro; Richard Noble

5d. PROJECT NUMBER
E60807

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Undersea Warfare Center Detachment,New London,CT,06320

8. PERFORMING ORGANIZATION REPORT NUMBER
TM 931059

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Space and Naval Warfare Command

10. SPONSOR/MONITOR'S ACRONYM(S)
SPAWAR PMW 182-52

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
TM 931059

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
NUWC2015

14. ABSTRACT
Three pneumatically controlled, seismic acoustic sources were evaluated at the Naval Undersea Warfare Center's Seneca Lake Test Facility during November 1992. The three acoustic sources, (a) a 1-cubic inch water gun, (b) a 10-cubic inch air gun, and (c) a 20-cubic inch air gun, were manufactured, furnished and operated by Bolt Technology Corporation of Norwalk, Connecticut These tests were conducted to examine the characteristics of the acoustic signals generated by each unit (e.g., source level, spectral content, waveform structure) and to characterize the emitted acoustic signals as a function of water depth and frequency. The purpose for conducting these evaluations was to determine if pneumatically controlled acoustic sources are suitable for making low frequency, shallow water volume scattering measurements in lieu of using SUS explosive charges. Analysis of these results indicate that neither the water gun nor the air guns tested can attain the spectral levels required for a shallow water volume scattering measurement. However, the data acquired may be used to scale these sources to yield the appropriate output levels.

15. SUBJECT TERMS
seismic acoustics; Seneca Lake; Bolt Technology Corporation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**35**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

ABSTRACT

Three pneumatically controlled, seismic acoustic sources were evaluated at the Naval Undersea Warfare Center's Seneca Lake Test Facility during November 1992. The three acoustic sources, (a) a 1-cubic inch water gun, (b) a 10-cubic inch air gun, and (c) a 20-cubic inch air gun, were manufactured, furnished and operated by Bolt Technology Corporation of Norwalk, Connecticut. These tests were conducted to examine the characteristics of the acoustic signals generated by each unit (e.g., source level, spectral content, waveform structure) and to characterize the emitted acoustic signals as a function of water depth and frequency. The purpose for conducting these evaluations was to determine if pneumatically controlled acoustic sources are suitable for making low frequency, shallow water volume scattering measurements in lieu of using SUS explosive charges. Analysis of these results indicate that neither the water gun nor the air guns tested can attain the spectral levels required for a shallow water volume scattering measurement. However, the data acquired may be used to scale these sources to yield the appropriate output levels.

ADMINISTRATIVE INFORMATION

This project was performed under NUWC Project Number E60807. The Principal Investigator is Mr. M.J. Vaccaro (Code 3112) and the Program Manager is Mr. R.G. Malone, (Code 33A). The sponsoring activity is the Space and Naval Warfare Command (SPAWAR PMW 182-52, Mr. C.I. Bohman).

ACKNOWLEDGEMENTS

The authors would like to acknowledge the on-sight support provided by Mr. Bogan Kawejsza for the operation, maintenance and testing of three Bolt Technology Corporation seismic sources during November 1992 at the NUWC Seneca Lake Test Facility. The authors would also like to acknowledge the helpful technical discussions held with Dr. Michael Sundvik, NUWC Code 3112, the analysis assistance provided by Mr. Paul Chelminski, Bolt Technology Corporation, the assistance provided during the testing by Messrs. Mark Jarret and Nelson Letourneau of The Naval Oceanographic Office, Code OAP, and the editing services performed by Mr. Salvatore Santaniello of Planning Systems Incorporated.

TABLE OF CONTENTS

Topic	Page
ABSTRACT	i
ADMINISTRATIVE INFORMATION	i
TABLE OF CONTENTS	ii
LIST OF ILLUSTRATIONS	iii
LIST OF TABLES	v
1.0 INTRODUCTION	1
2.0 BACKGROUND	1
3.0 SENECA LAKE TEST PROCEDURES	3
4.0 ANALYSIS AND RESULTS	4
4.1 Seismic Source Acoustic Signature and Repeatability	4
4.2 Depth Dependence of Acoustic Characteristics	4
Water Gun	4
Air Gun	6
4.3 Volume Dependance of an Air Gun	7
4.4 Directivity of Seismic Sources	7
4.5 Variability in Near-Field/Far-Field Source Level Determinations	8
Water Gun	8
Air Gun	8
5.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS	8
6.0 REFERENCES	28

LIST OF ILLUSTRATIONS

Figure	Caption	Page
1	Notional concept (top) and expected modes of operation (bottom) for proposed low frequency, shallow water volume (biological) scattering measurement system	11
2	Required source level spectrum for proposed low frequency,shallow water volume scattering measurement system	12
3	Test set-up for the Seneca Lake air/water gun evaluations	12
4	Acoustic pressure signature of (a) 1-in^3 water gun, (b) 10-in^3 air gun and (c) 20-in^3 air gun at test depth of 100 m [air drive-pressure = 3000 psi]	13
5a	Consistency of acoustic signature for 10 consecutive 1-in^3 water-gun transmission at a test depth of 50 m [air drive-pressure = 3000 psi]	14
5b	Consistency of acoustic signature for 5 consecutive 10-in^3 air-gun transmissions at a test depth of 50 m [air drive-pressure = 3000 psi]	15
5c	Consistency of acoustic signature for 5 consecutive 20-in^3 air-gun transmissions at a test depth of 50 m [air drive-pressure = 3000 psi]	15
6	Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 10 m [air drive-pressure = 3000 psi]	16
7	Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 25 m [air drive-pressure = 3000 psi]	16
8	Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 50 m [air drive-pressure = 3000 psi]	17
9	Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 75 m [air drive-pressure = 3000 psi]	17
10	Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 100 m [air drive-pressure = 3000 psi]	18
11	Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 125 m [air drive-pressure = 3000 psi]	18
12	Depth dependence of 1-in^3 water gun output based on peak pressure and total radiated energy of near-field receptions [air drive-pressure = 3000 psi]	19

LIST OF ILLUSTRATIONS (continued)

Figure	Caption	Page
13	Pressure and spectrum source level characteristics of 20-in^3 air-gun transmission at a test depth of 10 m [air drive-pressure = 3000 psi]	20
14	Pressure and spectrum source level characteristics of 20-in^3 air-gun transmission at a test depth of 25 m [air drive-pressure = 3000 psi]	20
15	Pressure and spectrum source level characteristics of 20-in^3 air-gun transmission at a test depth of 50 m [air drive-pressure = 3000 psi]	21
16	Pressure and spectrum source level characteristics of 20-in^3 air-gun transmission at a test depth of 100 m [air drive-pressure = 3000 psi]	21
17	Pressure and spectrum source level characteristics of 20-in^3 air-gun transmission at a test depth of 125 m [air drive-pressure = 3000 psi]	22
18	Depth dependence of 20-in^3 air gun output based on peak pressure and total radiated energy of near-field receptions [air drive-pressure = 3000 psi]	22
19	Depth dependence of 20-in^3 air gun resonant frequency based on reciprocal of initial bubble pulse period compared to prediction based on overburdening hydrostatic pressure [5]	23
20a	1-in^3 water gun longitudinal transmit beampattern based on peak and total energy	24
20b	1-in^3 water gun azimuthal transmit beampattern based on peak and total energy	24
21a	20-in^3 air gun longitudinal transmit beampattern based on peak and total energy	25
21b	20-in^3 air gun azimuthal transmit beampattern based on peak and total energy	25
22	Depth dependence of output level for 1-in^3 water gun based on peak pressure and total radiated energy processing of near- and far-field acoustic energy	26
23	Depth dependence of Source level for 20-in^3 air gun based on peak pressure and total radiated energy processing of near- and far-field acoustic energy	27

LIST OF TABLES

Figure	Title	Page
I	EXPECTED PEAK SOURCE LEVEL FOR 10- AND 20-CUBIC INCH AIR GUNS	7
II	SUMMARY OF SENECA LAKE TEST DATA FOR BOLT TECHNOLOGY CORPORATION SEISMIC SOURCES	9

1.0 INTRODUCTION

Three pneumatically controlled seismic acoustic sources were evaluated at the Naval Undersea Warfare Center's Seneca Lake Test Facility during November 1992. These seismic sources, (a) a 1-cubic inch water gun, (b) a 10-cubic inch air gun, and (c) a 20-cubic inch air gun, were manufactured, furnished and operated by Bolt Technology Corporation of Norwalk, Connecticut. Tests were conducted to examine the characteristics of the acoustic signals generated by each unit (e.g., source level, spectral content, waveform structure) and to characterize the emitted acoustic signals as a function of water depth and frequency. The purpose for conducting these evaluations was to determine if pneumatically controlled acoustic sources are suitable for making low frequency, shallow water volume scattering measurements in lieu of using SUS explosive charges.

2.0 BACKGROUND

Deep water measurements of low frequency volume scattering as a function of water depth are usually conducted based on a technique developed by Stockhausen and Figoli. [1] For that technique, a Vertical Line Array (VLA) is deployed to a depth of ≈750 m and SUS (Signal, Underwater Sound) Mk 59, 4 lb explosive charges are used as the acoustic source and set to detonate at a depth of ≈910 m; i.e., ≈160 m directly below the array. An upward-looking endfire acoustic beam is formed with the VLA to make direct path measurements of the volume scattering strength (S_V) over the upper 600 m of the water column. This experimental configuration results in a vertically *bistatic* test geometry. When considering the acquisition of *shallow water* S_V data, it becomes apparent that it would be best to employ a vertically *monostatic* test geometry because of the lack of sufficient water depth. However, the use of explosive sources for the monostatic test geometry is unacceptable due to the possibility of damaging the VLA.

Thus, a technique has been proposed [2] for measuring low frequency, shallow water (<400 m) volume scattering strength where a short VLA and an air gun or water gun (i.e., a broadband acoustic source) are collocated as part of a vertically suspended measurement system. The notional concept of the proposed system is depicted in the top panel of Figure 1. An upward looking endfire beam can easily be steered using the VLA and the reverberant acoustic signals can be processed to yield S_V as a function of water depth and frequency by incorporating the data processing procedures developed for the deep water acquisition technique.

Under the deep water *bistatic* test geometry the VLA is located deep in the water column and high intensity SUS charges are necessary in order to maintain a sufficient reverberation-to-noise level over the depth extent of the measurements. For the shallow water *monostatic* test geometry, significantly less source level is required and, thus, using a low frequency broadband air or water gun as the acoustic source is worthy of consideration. In addition, using a seismic source for shallow water S_V measurements eliminates the need to carry explosives aboard ship and avoids safety problems.

The sketches shown in the bottom panel of Figure 1 depict the two modes of suspension that would be employed to gather low frequency, shallow water volume scattering strength data using the vertically monostatic test geometry. For Mode #1 where the system is close to the sea surface, the surface return would arrive before the bottom return and acoustic energy scattered from biologics in the near-surface region would arrive before the surface reflected signal was received. For Mode #2 where the system is located around mid-water, the bottom return would arrive before the surface return and the acoustic energy scattered from a deeper biological strata in the water column would arrive before the the bottom reflected signal was received.

In considering the use of an air or water gun as the acoustic source for the proposed measurement approach, it was first necessary to determine the source spectrum levels required to ensure a sufficient reverberation-to-noise ratio based on a volume whose scattering strength is -85 dB//m^3 at a range of 300 m. Shown in Figure 2 is the modeled acoustic source spectrum required for the proposed shallow water volume scattering strength measurement system. This modeled result is based on the forming of an upward-looking endfire beam using a 16-element array having a half-wavelength element spacing at the design frequency of 1500 Hz. At 1500 Hz the half-beamwidth of the endfire beam is 19.7^o. The ambient noise level used to estimate the required spectrum was assumed to be that expected for a nominal sea state of '3'. Also, a 3 dB reverberation-to-ambient noise detection threshold was used. As indicated in Figure 2, the required nominal source spectrum levels range between 155 to 165 dB//uPa^{2}sec/Hz from 200-to-1100 Hz.

Thus, the specific goal of the Seneca Lake evaluations was to determine if the Bolt Technology Corporation air and water gun seismic acoustic sources were capable of producing the required energy spectrum levels shown in Figure 2, at water depths on the order of those shown in Figure 1. Therefore, broadband source level measurements were made over the full depth extent possible at Seneca Lake, i.e., from the surface to 125 m. Realizing that a typical operating depth of a seismic source for the proposed monostatic test geometry would be on the order of 200 m, data were acquired at intermediate depth intervals from 0 to 125 m in order to facilitate scaling of the energy spectrum level at the expected maximum operating depth.

3.0 SENECA LAKE TEST PROCEDURES

The procedures used to evaluate the three Bolt Technology seismic sources are delineated in the test plan used at Seneca Lake. [3] A block diagram of the test set up is presented in Figure 3. The high pressure air for these pneumatic sources was supplied using a gasoline powered compressor furnished by Bolt Technology Corporation. Tests were conducted on each of the three sources, i.e., a 1-cubic inch water gun, a 10-cubic inch air gun, and a 20-cubic inch air gun, using internal drive pressures of both 2000 and 3000 psi. Excitation of the sources was regulated using the FC-100 firing controller. Data were acquired to ascertain the acoustic characteristics of each source (e.g., source level, energy spectrum, waveform characteristics) at water depths of 10, 25, 75, 100 and 125 meters. Typically, 10 excitations occurred at each depth to assess the repeatability of the transmitted acoustic signature. Two Naval Research Laboratory, Underwater Sound Reference Detachment Model F37 reference hydrophones were simultaneously lowered in depth with each source, one located at a distance of 1 m and the other at 10 m from the source; i.e., one in the near-field and one in the far-field. The nominal receiving sensitivity of the reference hydrophones was -206.2 dB//V/uPa.

Acoustic signals received via each hydrophone were passed through a 50-2500 Hz bandpass filter when the water gun was under evaluation and a 32-2500 Hz bandpass filter when the air guns were under evaluation. The received signals were digitized using a MACADIOS 12-bit analog-to-digital converter (ADC) which was contained in a Macintosh IIx personal computer. The ADC sampling rate was 10 kHz and the digitized time series for each event was stored on floppy disk for later processing and analysis. Processing of the received time series was performed using a Macintosh mathematical applications software package known as MATLAB, developed by The MathWorks, Inc. Each recorded near-and far-field time series was processed to yield calibrated source levels, acoustic signatures, energy spectra and total radiated energy.

In addition to the source characterization measurements described above, 2-axis directivity patterns were obtained for the 1-cubic inch water gun and the 20-cubic inch air gun. For these measurements, each source was rigidly mounted to a rotator and lowered to a depth of 37 m. The test hydrophone was located at a distance of 15 m. The broadband signal level was measured at 15-degree increments in angle about the longitudinal and azimuthal axes of the source as it was rotated. Both the peak and total energy of the received signal was calculated at each incremental angle using waveform statistics algorithms of the SuperScope applications software package developed by GW Instruments, Inc. for the Macintosh personal computer.

4.0 ANALYSIS AND RESULTS

4.1 Seismic Source Acoustic Signature and Repeatability

Shown in Figures 4a, 4b and 4c are the recorded near-field time series for the 1-cubic inch water gun, 10-cubic inch air gun, and 20-cubic inch air gun, respectively, acquired at a water depth of 100 m using an air drive-pressure of 3000 psi. The 100 m depth results are chosen for discussion because the received signal was not contaminated by other acoustic multipath arrivals. Since a 10 kHz sampling rate was used for digitization, the time resolution for reproducing the acoustic signals is more than sufficient since 100 values of pressure level are contained over each 10 msec increment of the time series plots.

It is evident from Figures 4a, 4b and 4c that the acoustic pressure-signature for the water gun is markedly different from those for the air guns. The water gun signature portrays an impulse response with insignificant bubble pulse activity, while the air gun signatures portray a number of bubble-pulse oscillations. These differences in acoustic signature between the two types of pneumatic sources were observed at all depths. As will be shown later, the acoustic signature is exceedingly depth dependent for both types of sources.

Shown in Figure 5a is a set of 10 consecutive acoustic pulses generated with the 1-cubic inch water gun while Figures 5b and 5c each contain 5 consecutive acoustic pulses generated with the 10- and 20-cubic inch air guns, respectively. Each pressure time series was recorded using the near-field hydrophone. For these results, the pneumatic sources were positioned at a water depth of 50 m and the air drive-pressure was 3000 psi. It is clear from these plots that all three sources yield a highly repeatable acoustic pressure signature. It should be noted that the air gun time series presented in Figures 5b and 5c contain a multipath arrival resulting in an interference effect that alters the bubble pulse decay rate. Similar analysis was performed regarding the repeatability of the acoustic signature as a function of water depth and there was excellent repeatability in acoustic signature at all test depths.

4.2 Depth Dependence of Acoustic Characteristics

Water Gun

Presented in Figures 6 through 11 are averaged near-field time series, and associated energy spectra, generated with the 1-cubic inch water gun at water depths of 10, 25, 50, 75, 100 and 125 meters, respectively. An internal air pressure of 3000 psi was used in all cases. Each figure portrays a mean time series [solid line] for a set of 10 consecutive transmissions at each water depth along with the standard deviation [dashed line]. The repeatability of the

acoustic signature is also apparent in these plots because of the small standard deviation. However, both the temporal and spectral characteristics of the water gun change dramatically as a function of water depth. Listed below are qualitative observations regarding the depth dependent characteristics of this acoustic source.

- The peak output pressure and spectrum levels decrease with increasing water depth; i.e., the broadband peak level decreases by 35 dB, from 217 to 181.5 dB//μPa@1m, over a water depth change of 10 m to 125 m.
- The temporal character of the acoustic pressure varies extensively with water depth.
- The time delay between the precursor and primary acoustic pulses decreases with water depth.
- The peak level of the precursor tends to increase with water depth except that it appears to be absent at the depth of 125 m.
- Bubble pulse oscillations occur as the source is lowered to deeper depths and the character of the oscillations changes dramatically beyond 75 m where the period increases by an order of magnitude at depths between 100 and 125 m.
- In general, the effective bandwidth decreases with increasing depth. However, the high frequency roll-off characteristics vary extensively over the test depths and no first order scaling law seems to apply.
- Spectral notching is apparent at operating depths of 75, 100 and 125 m and is likely attributable to increased bubble pulse activity.
- A 'spectral knee' is apparent around 100 Hz for results at all depths and a low frequency roll-off of approximately 12 dB per octave is observed below this knee at the shallow depths. At deeper operating depths, the rate of spectral roll-off increases.

In describing the near-field acoustic pressure signature of a 'large' water gun, Parkes and Hatton [4] show *negative* going precursor and primary acoustic pulses — a result which is essentially 180° out of phase from those presented in Figures 6 and 7 for the shallower test depths. Initially, it was thought that this could be caused by a wiring polarity reversal in the measurements test set-up. However, this was discounted because previous measurements made by Bolt Technology Corporation on the water gun tested at Seneca Lake also showed positive going precursor and primary acoustic pulses, as do published results for similar water guns. [5]

The depth dependence of source level for the 1-cubic inch water gun is quantitatively shown in Figure 12. It is evident that both the peak output pressure (dB//μPa@1m) and total radiated energy (dB//μPa^{2}sec) decrease by 35 and 27 dB, respectively, as operating depth changes from 10 to 125 m.

Air Gun

Shown in Figures 13 through 17 are averaged near-field time series, and associated energy spectra, generated with the 20-cubic inch air gun source for water depths of 10, 25, 50, 100 and 125 meters, respectively. An internal air pressure of 3000 psi was used in all cases. Each figure portrays a mean time series [solid line] for a set of 5 consecutive transmissions at each water depth along with the standard deviation [dashed line]. Time constraints precluded acquisition of more data for the averaging process. The repeatability of the acoustic signature is also apparent in these plots based on the small standard deviation. However, both the temporal and spectral characteristics of the air gun change dramatically with water depth.

The acoustic pressure signature is rich in bubble pulse activity at all depths. The period of the bubble pulse tends to decreases with water depth and this effect translates into an increase in frequency of the peak level of the energy spectrum; i.e., an increase in the resonant frequency. Further, the bubble pulse activity associated with the air guns results in significantly less bandwidth compared to that of the water gun. The higher frequencies of the air gun spectrum tend to be attenuated. The high frequency roll-off due to this attenuation is on the order of 10 to 12 dB per octave. Spectral notching appears to only be significant for the 100 and 125 m test depth results — an unexpected and presently unexplained effect.

As can be observed in Figure 18, the depth dependence of the source level for the 20-cubic inch air gun is markedly different from that of the water gun. The striking difference is the consistency in source level as a function of water depth for the air gun where the source level of the water gun decreases with depth. Peak pressure level is on the order of 221 dB//μPa@1m at all depths, while the total energy level is on the order of 195 dB//μPa^2sec. It should be noted that the total energy levels at tests depths less then 50 m may be somewhat reduced because of the truncation that was applied to alleviate multipath effects when processing the pressure time series.

Plotted in Figure 19 is the resonant frequency (i.e., peak in energy spectrum) observed at each test depth for the 20-cubic inch air gun source using an internal air pressure of 3000 psi. Parkes and Hatton [4] state that the initial bubble pulse period of the signal generated by an air gun is proportional to overburdening hydrostatic (ambient) pressure raised to the 5/6 power; i.e., $(P_{ambient})^{5/6}$. Assuming that the inverse of the first bubble pulse period essentially characterizes the spectral resonance, the functional dependence on resonance frequency is expected to be proportional to $(P_{ambient})^{5/6}$. This functional dependence is plotted as a dashed line on Figure 19 with an arbitrary scaling constant to approximate the measured data.

4.3 Volume Dependence of an Air Gun

According to Parkes and Hatton [4] the primary or peak amplitude (A) of an air gun is proportional to internal volume (V) raised to the 1/3 power; i.e., $A = C_1 V^{1/3}$ where C_1 is a constant. Thus, in logarithmic space a doubling of the internal volume results in an increased primary amplitude squared of $20\text{Log}(2^{1/3})$ or 2 dB. Shown in Table I are calculations of the primary amplitude squared (source level) for both the 10- and 20-cubic inch air guns at source depths of 50 and 100 m.

TABLE I

EXPECTED PEAK SOURCE LEVEL FOR
10- AND 20-CUBIC INCH AIR GUNS

Source Depth m	SL [10-in^3] dB//uPa@1m	SL [20-in^3] dB//uPa@1m	Change in SL dB//uPa@1m
50	220.8	221.3	0.5
100	220.9	221.7	0.8

The expected 2-dB increase in source level is not observed by doubling the internal volume of the air gun. Rather, the peak source level increases from 0.5 to 0.8 dB depending on operating depth. This result may have been affected by the use of a high pass filter during acquisition of data which attenuated the very low frequency energy generated by the air gun.

4.4 Directivity of Seismic Sources

Polar plots containing the longitudinal and azimuthal axes transmit beampatterns for the 1-cubic inch water gun are shown in Figures 20a and 20b, respectively. Each plot shows two beampatterns, one based on peak source level (solid line) and the other based on total energy source level (dashed line). About the longitudinal axis, the beampatterns for the water gun are essentially omnidirectional to within ±0.5 dB based on both the peak and total energy source level processing. About the azimuthal axis, the beampattern indicates that the source is slightly directional based on the peak source level response, being approximately 3 dB down from the Maximum Response Axis (MRA) value at 90°. However, based on the total energy source level, the beampattern is omnidirectional to within ±0.75 dB about the azimuthal axis.

Directivity measurements made on the 20-cubic inch air gun are shown in Figures 21a and 21b. For this source, the longitudinal and azimuthal axes transmit beampatterns are omnidirectional to within ±0.5 dB based on both peak and total energy processing.

4.5 Variability in Near-Field/Far-Field Source Level Determinations

Water Gun

Observing Figure 22, a comparison can be made between the source levels determined by processing acoustic signals received via the hydrophones positioned in the near- and far-fields of the 1-cubic inch water gun transmissions. In this figure, peak (square symbols) and total energy (circular symbols) source levels are plotted as a function of water depth. The far-field levels have been corrected for spreading loss to a unit distance from the source. The peak source level measured in the far-field is between 2.5 and 10.3 dB below the near-field values, depending on depth. The near-field/far-field difference is greatest at a source depth of 50 m. At this point it is not clear why the difference (or ratio) between the near- and far-field peak source level values varies to this degree as a function of water depth. In terms of total energy, there is little to no difference between near- and far-field source level determinations at all test depth, indicating that energy is conserved. From Figure 22, it can be inferred that the bandwidth of the far-field acoustic reception is slightly wider than that of the near-field reception, at the expense of a lower peak source level.

Air Gun

A comparison of near- and far-field source level determinations can be made for the 20-cubic inch air gun by viewing Figure 23. As in Figure 22, peak and total energy source level values are plotted for each test depth. For the air gun, far-field peak source levels are consistently below those of the near field — similar to the results observed for the water gun. However, the differences between near- and far-field peak source level values are significantly less than for the water gun, being on the order of 1 to 5 dB. There are slight differences between the near-and far-field total energy source level values for the air gun measurements. These differences could be attributable to multipath effects, particularly at the shallow operating depths where the acoustic path length from the source to the water surface is the least in comparison to the other test depths.

5.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Three seismic sources, (a) a 1-cubic inch water gun, (b) a 10-cubic inch air gun, and (c) a 20-cubic inch air gun, manufactured by Bolt Technology Corporation of Norwalk, Connecticut, were evaluated at the NUWC Seneca Lake Test Facility during November 1992. Tests were conducted to examine acoustic characteristics (e.g., source level, spectral content, waveform structure) and to characterize transmitted signals as a function of water depth. The purpose was to determine if pneumatically controlled seismic sources are suitable for making

low frequency, shallow water volume scattering strength measurements in lieu of using SUS explosive charges. If so, a proposed measurement procedure [2], where a seismic source and a vertical line array (VLA) receiver are collocated in the water column, could be used for shallow-water experiments vice the contemporary deep water VLA/SUS procedure. This would result in a *monostatic* test geometry vice a *bistatic* test geometry. A summary of the test data acquired at Seneca Lake is contained in Table II.

TABLE II

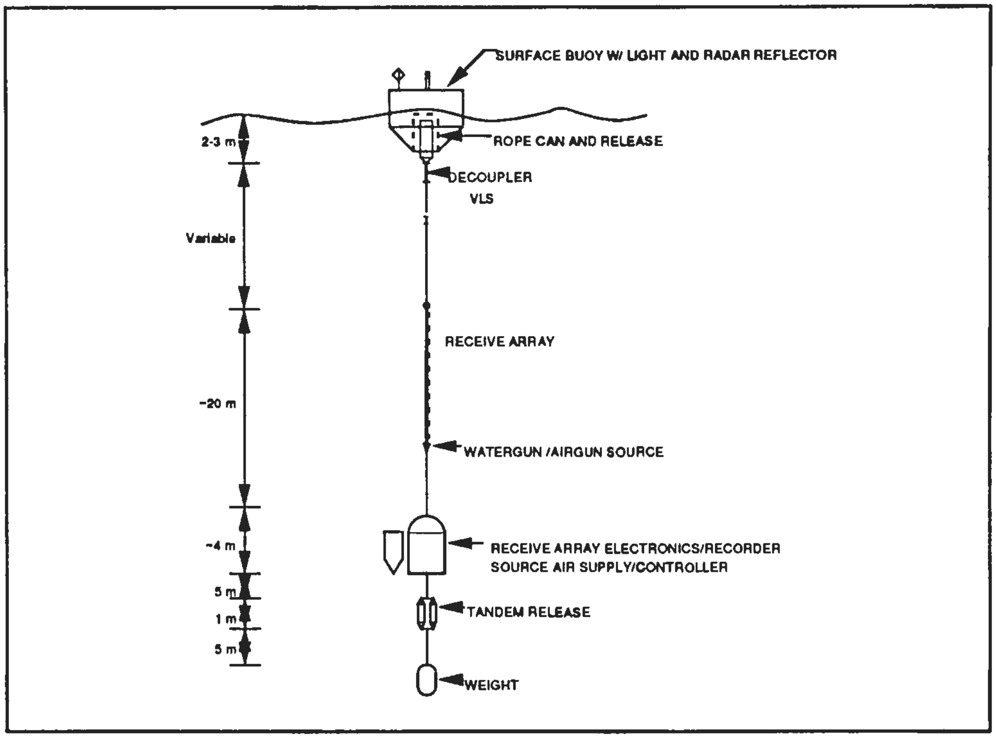
SUMMARY OF SENECA LAKE TEST DATA FOR
BOLT TECHNOLOGY CORPORATION SEISMIC SOURCES

				NEARFIELD				
SERIES NUMBER	GUN TYPE	OPERATING PRESSURE (psi)	OPERATING DEPTH (m)	BROADBAND PEAK (dB)	SPECTRAL PEAK (dB)	FREQ. @ SP. PEAK (Hz)	TOTAL RAD. ENERGY dB//uPa^2sec	NUMBER OF SHOTS AVERAGED
14	1 CU. IN WG	3000	10	216.9	156.5	185.5	181.7	10
13	1 CU. IN WG	3000	25	213.5	153.4	263.7	178.7	10
12	1 CU. IN WG	3000	50	211.8	148.6	603	175.8	10
11	1 CU. IN WG	3000	75	207.7	139.9	100.1	169.4	10
10	1 CU. IN WG	3000	100	193	138.1	80.57	158.3	10
9	1 CU. IN WG	3000	125	181.5	136.3	70.8	154.9	10
21	10 CU IN AG	3000	100	220.9	180.6	134.3		5
20	10 CU IN AG	3000	50	220.8	183.9	78.12		5
19	20 CU IN AG	3000	125	221.7	181.3	131.8	197.4	5
18	20 CU IN AG	3000	100	221.7	183.7	105	198.3	5
17	20 CU IN AG	3000	50	221.3	174.4	85.45	193.8	5
16	20 CU IN AG	3000	25	221.1	176.7	63.48	194.3	5
15	20 CU IN AG	3000	10	220.8	177.2	51.27	194	5

				FARFIELD				
SERIES NUMBER	GUN TYPE	OPERATING PRESSURE (psi)	OPERATING DEPTH (m)	BROADBAND PEAK (dB)	SPECTRAL PEAK (dB)	FREQ. @ SP. PEAK (Hz)	TOTAL RAD. ENERGY dB//uPa^2sec	NUMBER OF SHOTS AVERAGED
14	1 CU. IN WG	3000	10	212.5	156.9	205.1	180.2	10
13	1 CU. IN WG	3000	25	202.9	153.6	256.3	178.8	10
12	1 CU. IN WG	3000	50	201.5	148.2	593.3	175.4	10
11	1 CU. IN WG	3000	75	201	139.6	85.45	169	10
10	1 CU. IN WG	3000	100	190	137.8	90.33		10
9	1 CU. IN WG	3000	125	178.9	136.4	70.8	154.8	10
21	10 CU IN AG	3000	100	218.7	180.5	136.7		5
20	10 CU IN AG	3000	50	219.9	183.6	75.68		5
19	20 CU IN AG	3000	125	217.3	179.1	134.3	195.9	5
18	20 CU IN AG	3000	100	220.4	183.4	105	197.7	5
17	20 CU IN AG	3000	50	220	175.7	80.57	194.2	5
16	20 CU IN AG	3000	25	218.6	176.7	65.92	195.1	5
15	20 CU IN AG	3000	10	219.3	180.5	53.71	197.4	5

It appears from these test results that neither the water gun nor the air guns, in their present state of development, can attain the energy spectrum level requirements set forth in Figure 3. However, of the two types, the 20-cubic inch air gun comes closest to meeting that requirement. Although the 20-cubic inch air gun appears to be excessive in bubble pulse generation, the transmitted signal is highly repeatable in acoustic signature and spectral content at all Seneca Lake test depths from 10 m to 125 m. The energy spectrum level is greater than the requirement of ≈160 dB//uPa^{2}sec/Hz at frequencies below 300-400 Hz, depending on water depth, but is from 15-20 dB (i.e., ≈140 dB//uPa^{2}sec/Hz) below spectrum level requirements at frequencies from 400 to 1400 Hz. [The energy spectrum level of the water gun does not exceed 160 dB//uPa^{2}sec/Hz at any frequency and is highly attenuated at high frequencies as water depth increases.] Also, the source level of the air gun is relatively constant as a function of water depth, being above ≈193 dB//μPa^{2}sec, based on total radiated energy, and above ≈208 dB//μPa@1m based on peak pressure level. [The source level for the water gun decreases from ≈180 to ≈155 dB//μPa^{2}sec or from ≈212 to ≈180 dB//μPa@1m, based on total radiated energy and peak pressure level, respectively, as water depth increases from 10 to 125 m.] Further, the longitudinal and azimuthal transmit beampatterns of the 20-cubic air gun source are omnidirectional, while, for the water gun, the azimuthal transmit beampattern portrays a slight directionality (i.e., down by ≈3 dB at 90° from MRA) based on peak level processing only.

It may be possible to increase the source level and improve spectral response of these seismic sources through improvements in mechanical/pneumatic engineering characteristics and thus attain the energy spectrum level requirements set forth in Figure 3. However, since the repeatability in the acoustic pressure signature and spectral characteristic of each source has been shown to be excellent at a given water depth, it may be possible that the 20-cubic inch air gun can be used in its present state to successfully measure shallow water volume scattering simply by applying coherent signal processing procedures, such as replica correlation. Further, it is also apparent that it may be possible to employ this proposed collocated air-gun/VLA shallow water acoustic data acquisition system to conduct other environmental acoustic measurements such as surface/bottom backscattering, surface/bottom forward scattering and transmission loss measurements.



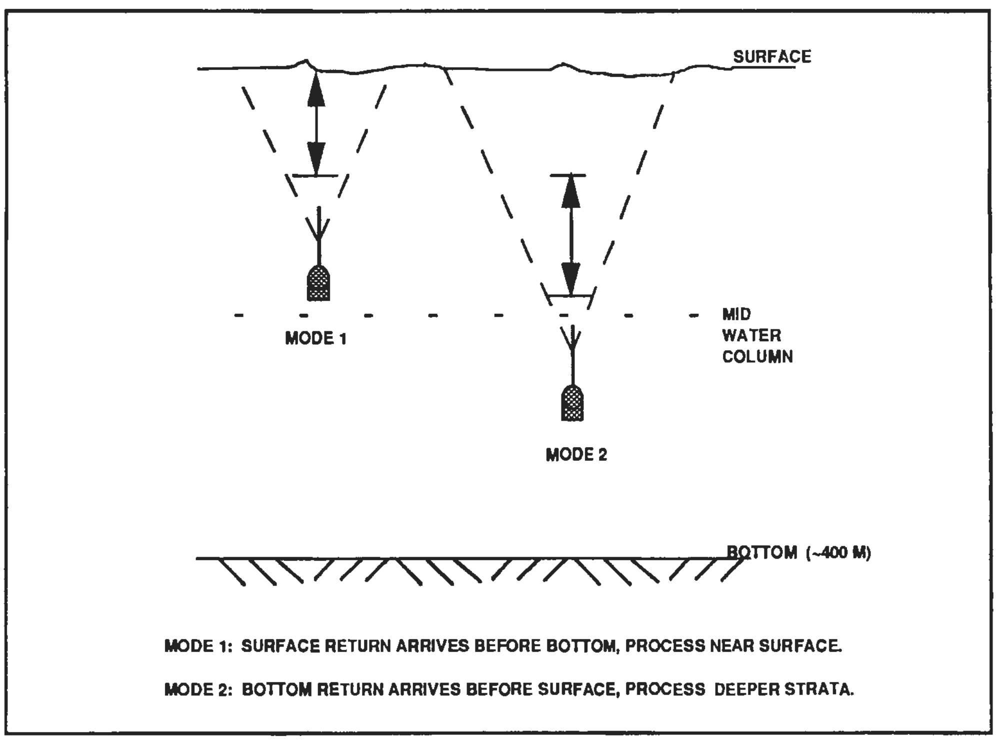


Figure 1. Notional concept (top) and expected modes of operation (bottom) for proposed low frequency, shallow water volume (biological) scattering measurement system.

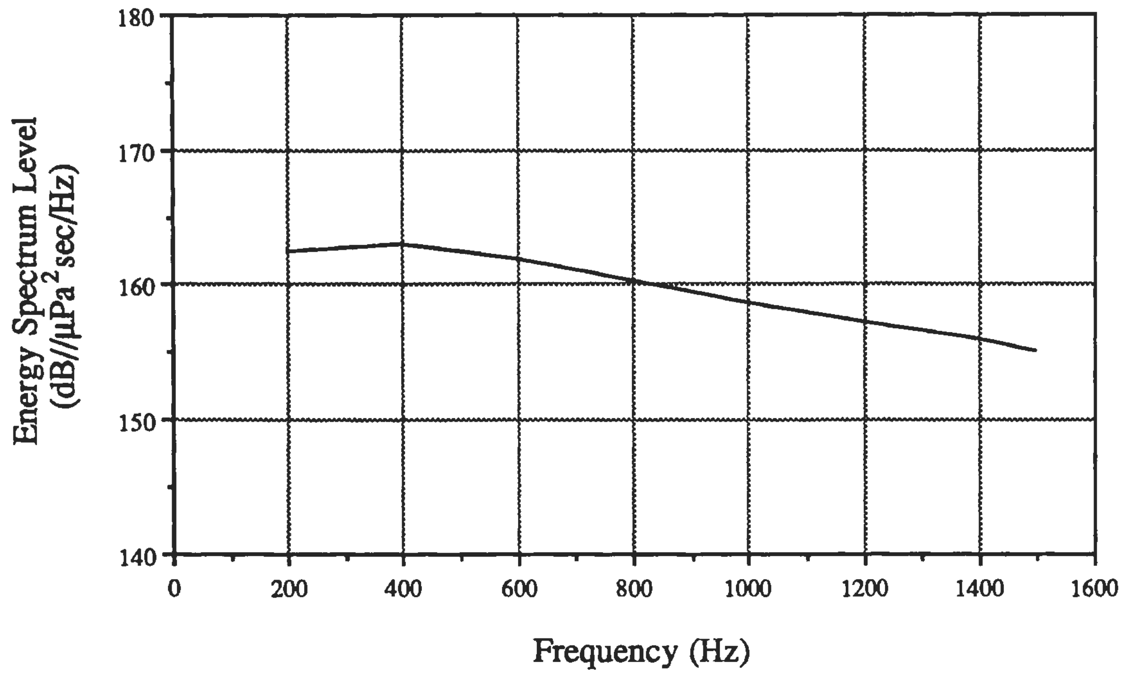


Figure 2. Required source level spectrum for proposed low frequency, shallow water volume scattering measurement system.

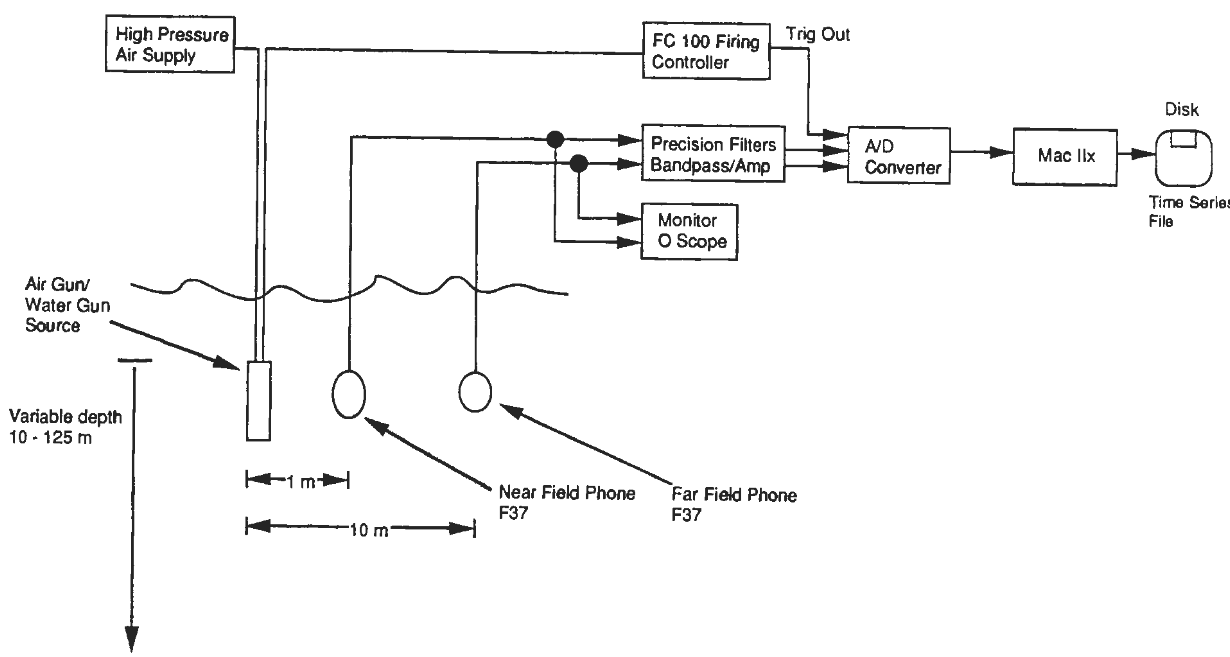


Figure 3. Test set-up for the Seneca Lake air/water gun evaluations.

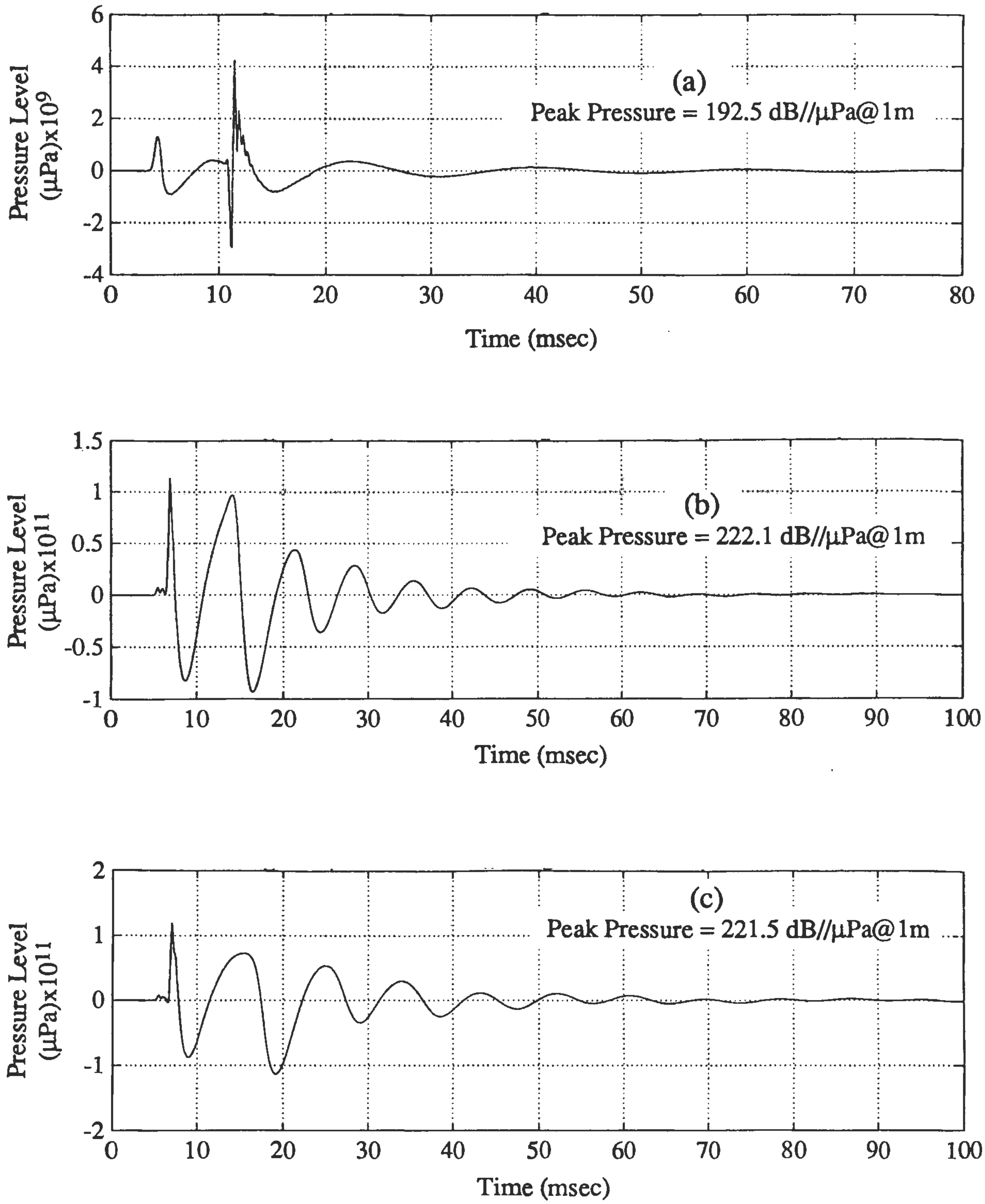


Figure 4. Acoustic pressure signature of (a) 1-in^3 water gun, (b) 10-in^3 air gun and (c) 20-in^3 air gun at test depth of 100 m [air drive-pressure = 3000 psi].

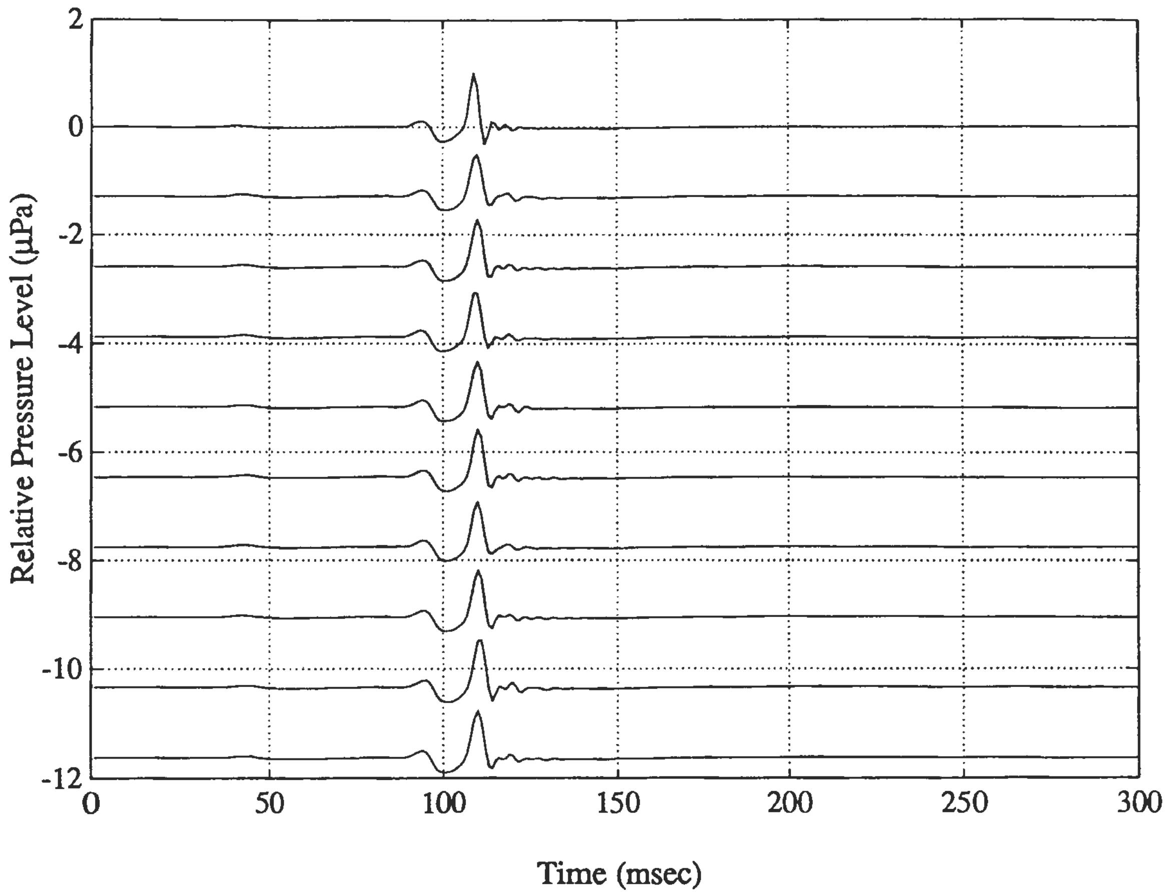


Figure 5a. Consistency of acoustic signature for 10 consecutive 1-in^3 water-gun transmission at a test depth of 50 m [air drive-pressure = 3000 psi].

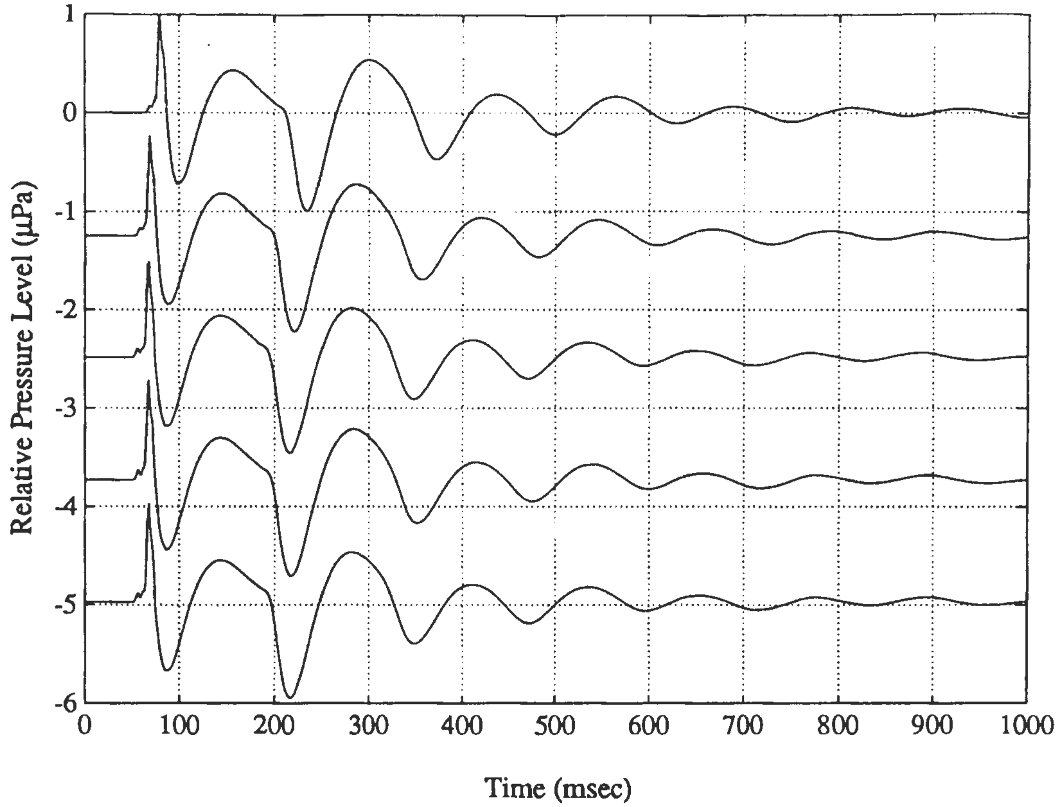


Figure 5b. Consistency of acoustic signature for 5 consecutive 10-in^3 air-gun transmissions at a test depth of 50 m [air drive-pressure = 3000 psi].

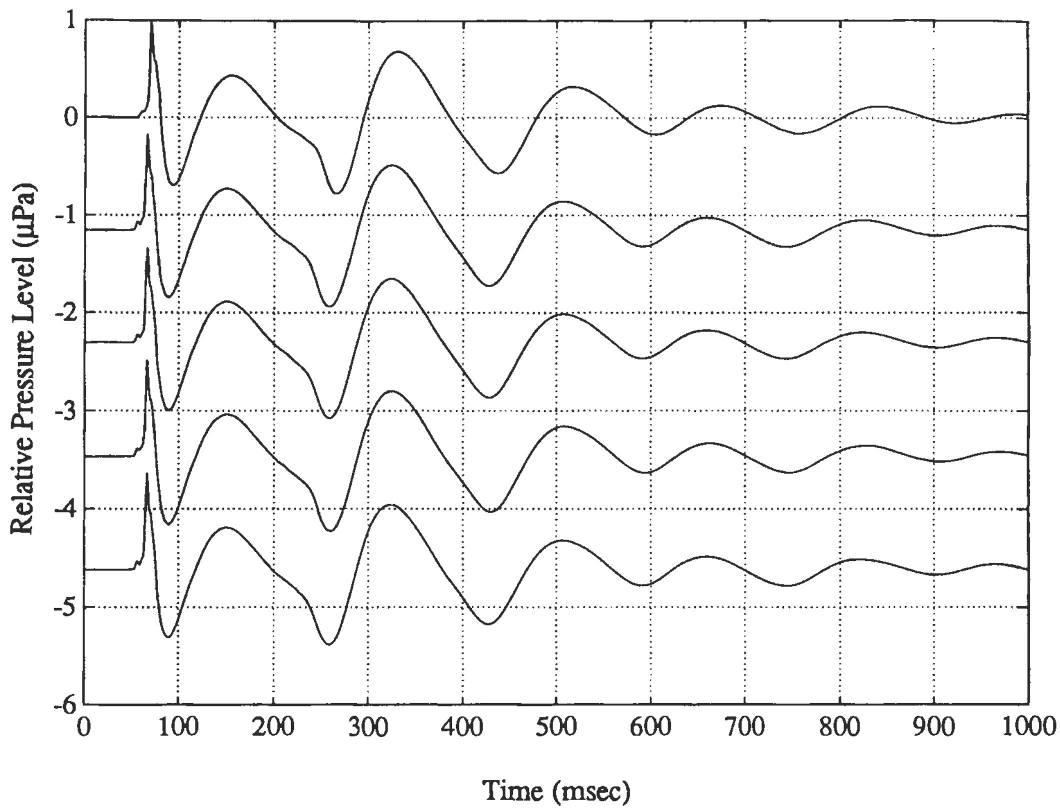


Figure 5c. Consistency of acoustic signature for 5 consecutive 20-in^3 air-gun transmissions at a test depth of 50 m [air drive-pressure = 3000 psi].

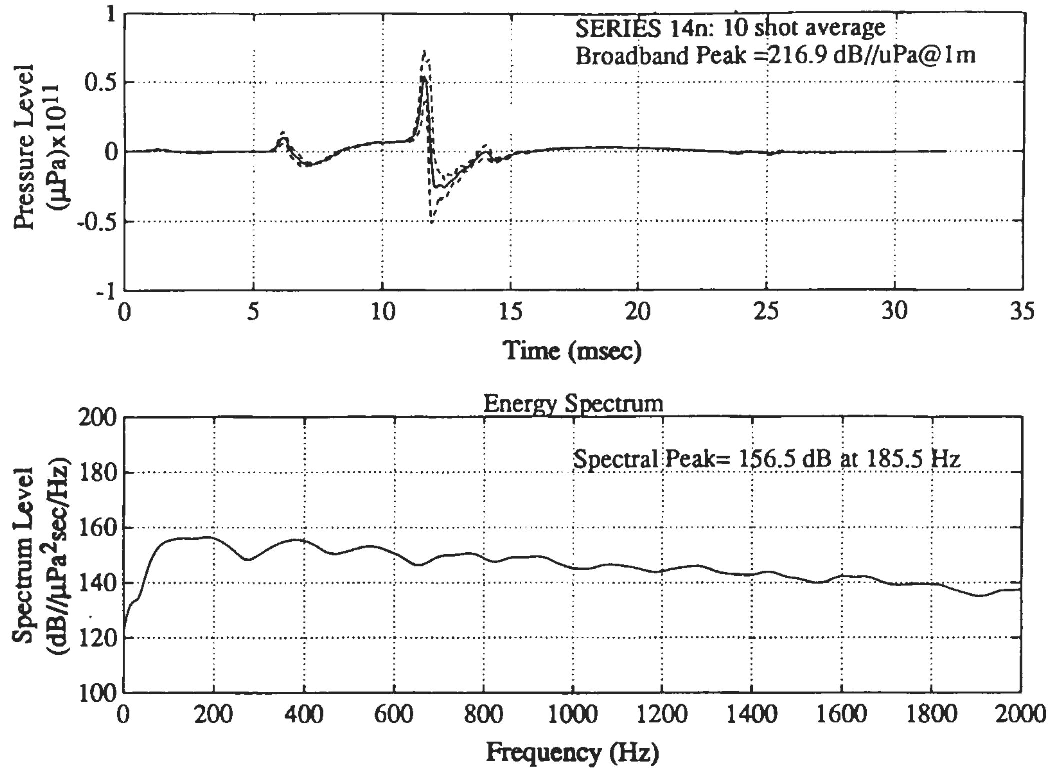


Figure 6. Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 10 m [air drive-pressure = 3000 psi].

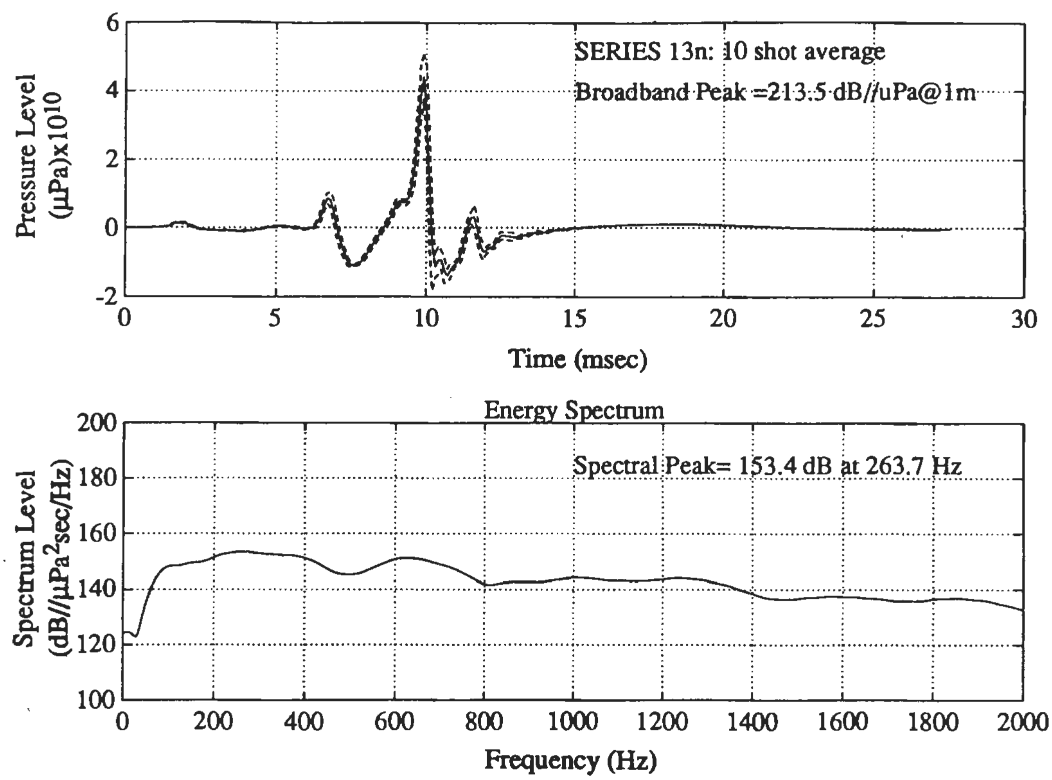


Figure 7. Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 25 m [air drive-pressure = 3000 psi].

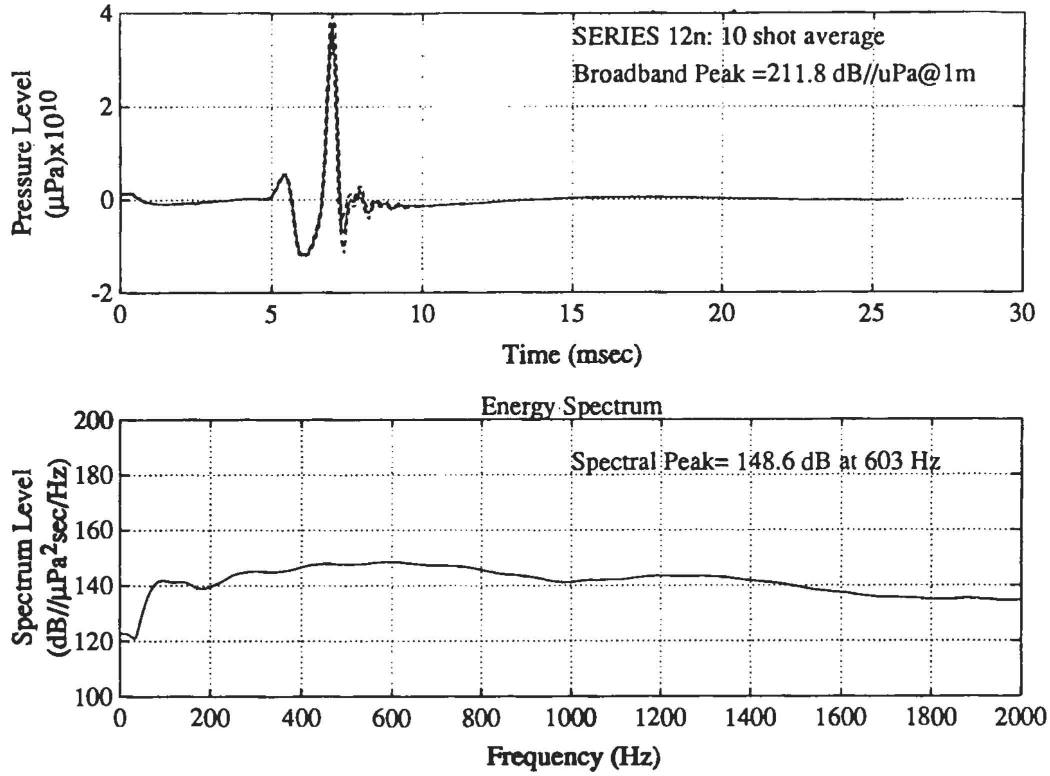


Figure 8. Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 50 m [air drive-pressure = 3000 psi].

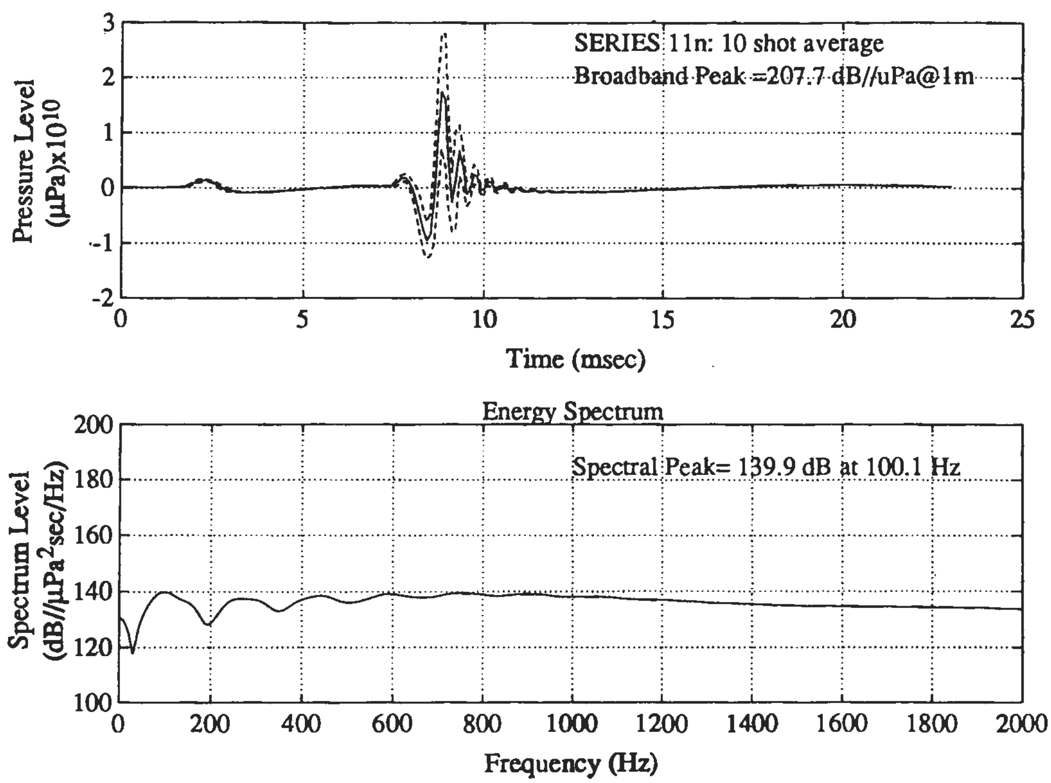


Figure 9. Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 75 m [air drive-pressure = 3000 psi].

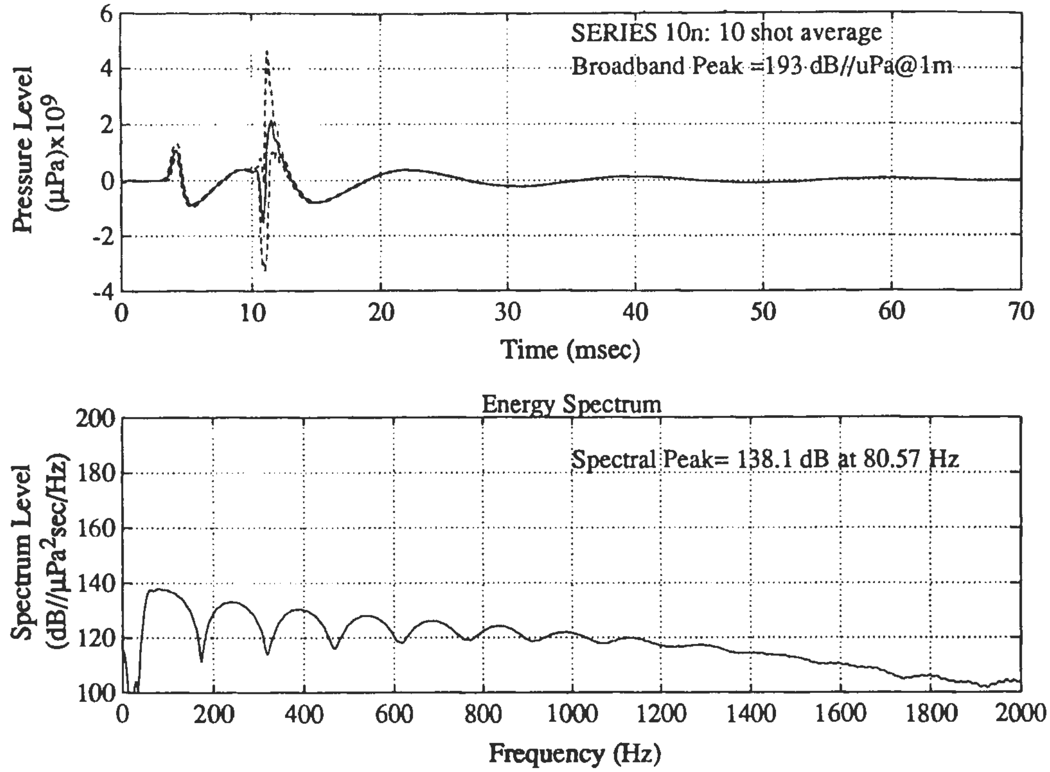


Figure 10. Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 100 m [air drive-pressure = 3000 psi].

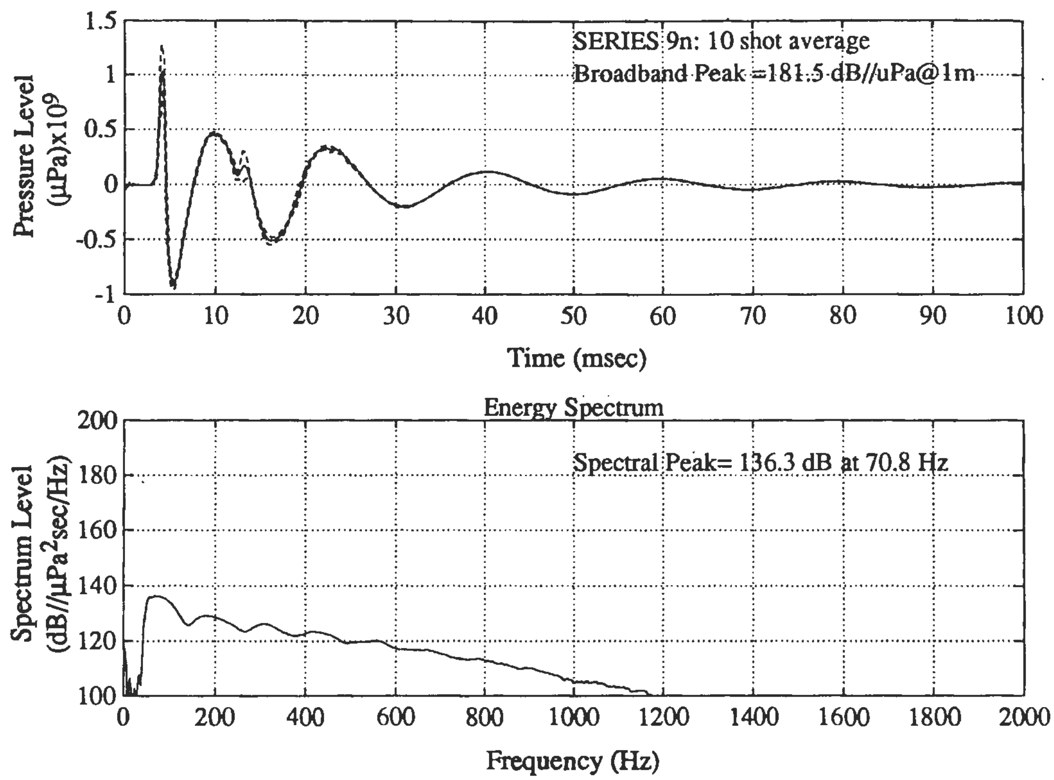


Figure 11. Pressure and spectrum source level characteristics of 1-in^3 water-gun transmission at a test depth of 125 m [air drive-pressure = 3000 psi].

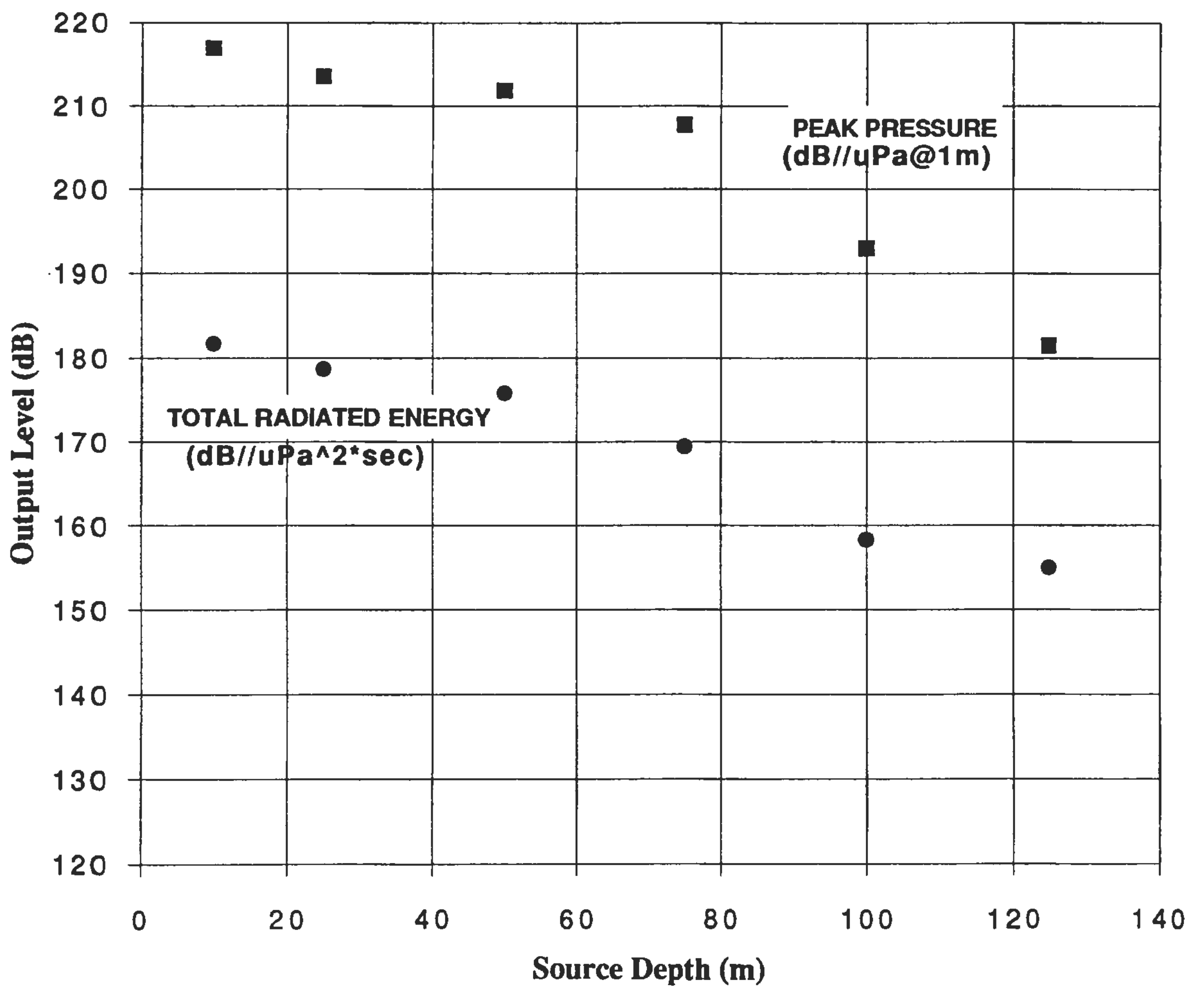


Figure 12. Depth dependence of 1-in^3 water gun output based on peak pressure and total radiated energy of near-field receptions [air drive-pressure = 3000 psi].

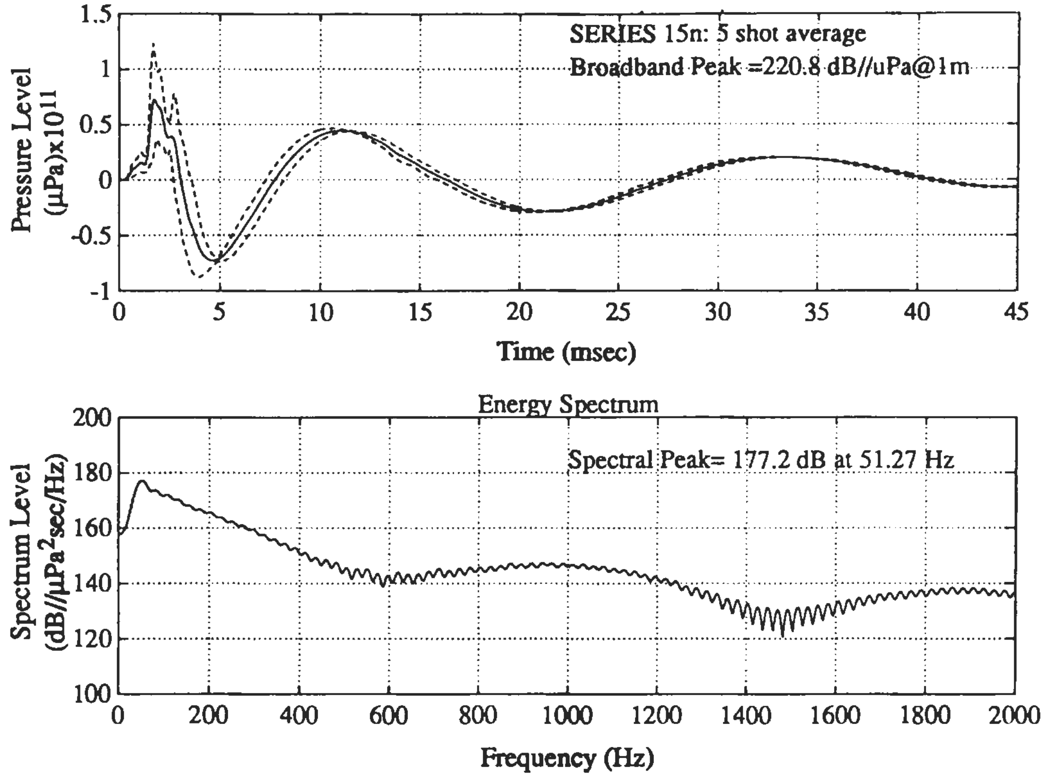


Figure 13. Pressure and spectrum source level characteristics of 20-in^3 air-gun transmission at a test depth of 10 m [air drive-pressure = 3000 psi].

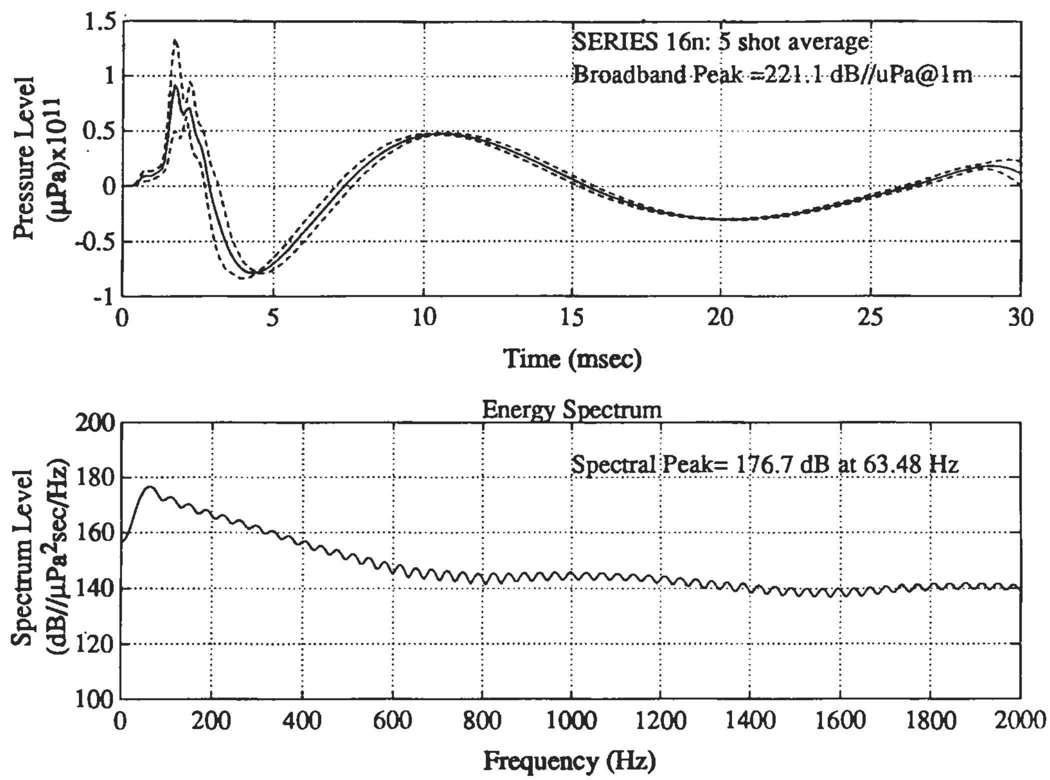


Figure 14. Pressure and spectrum source level characteristics of 20-in^3 air-gun transmission at a test depth of 25 m [air drive-pressure = 3000 psi].

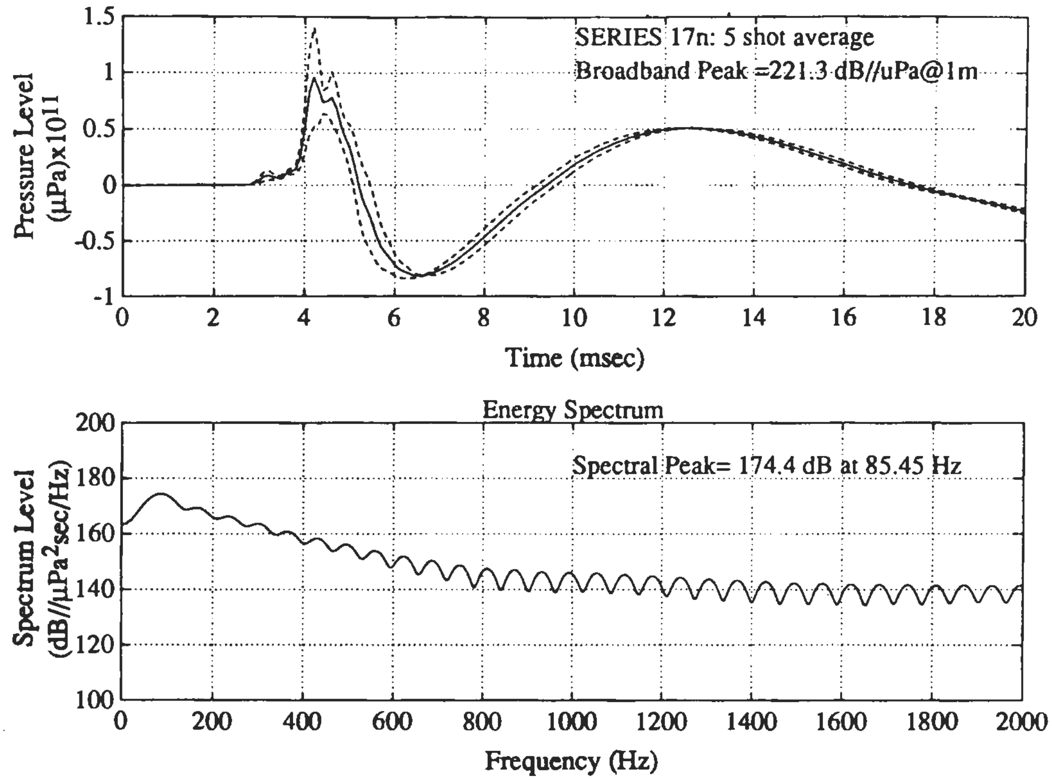


Figure 15. Pressure and spectrum source level characteristics of 20-in^3 air-gun transmission at a test depth of 50 m [air drive-pressure = 3000 psi].

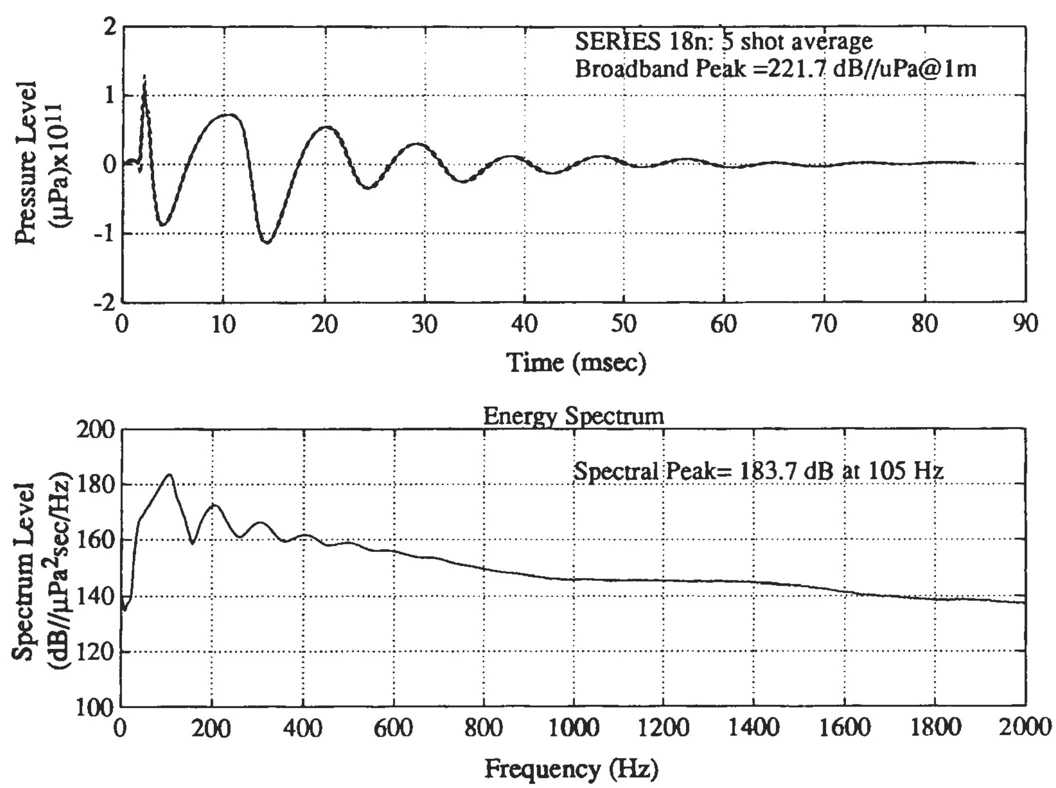


Figure 16. Pressure and spectrum source level characteristics of 20-in^3 air-gun transmission at a test depth of 100 m [air drive-pressure = 3000 psi].

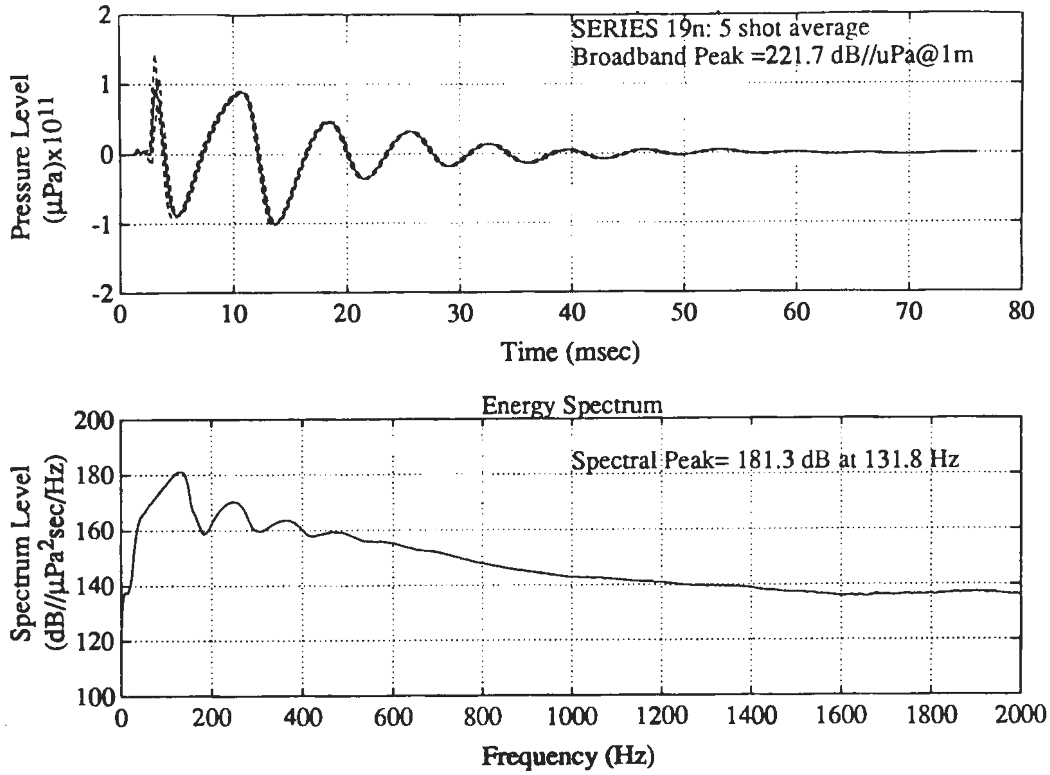


Figure 17. Pressure and spectrum source level characteristics of 20-in^3 air-gun transmission at a test depth of 125 m [air drive-pressure = 3000 psi].

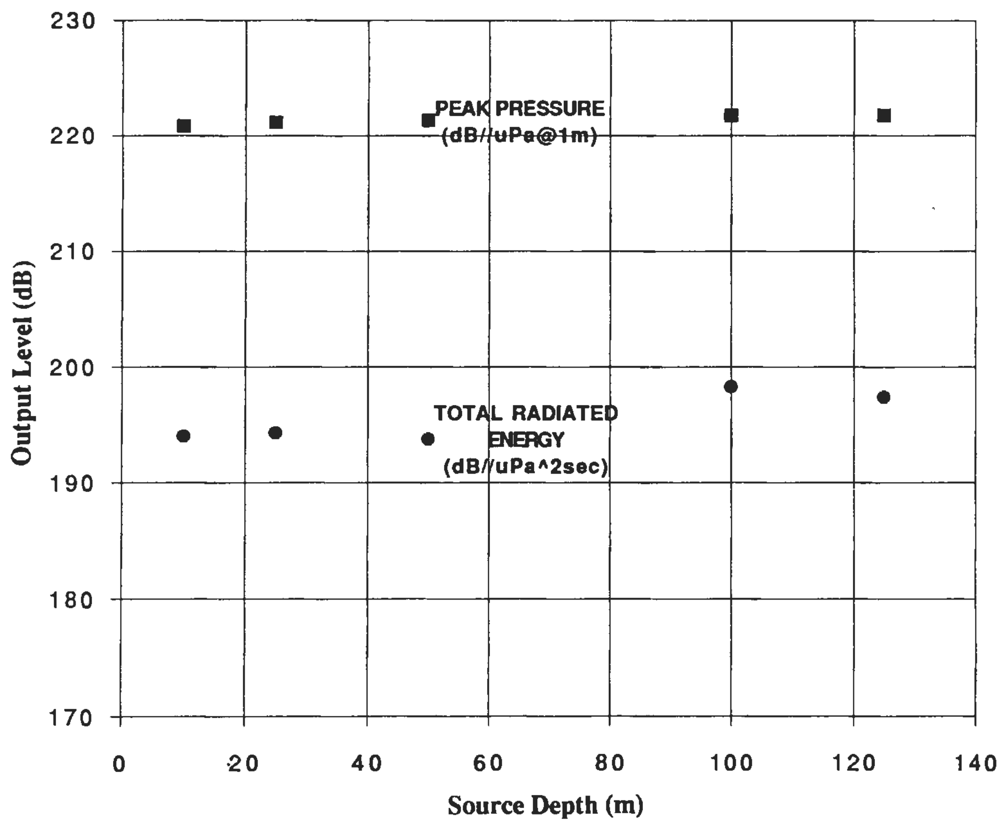


Figure 18. Depth dependence of 20-in^3 air gun output based on peak pressure and total radiated energy of near-field receptions [air drive-pressure = 3000 psi].

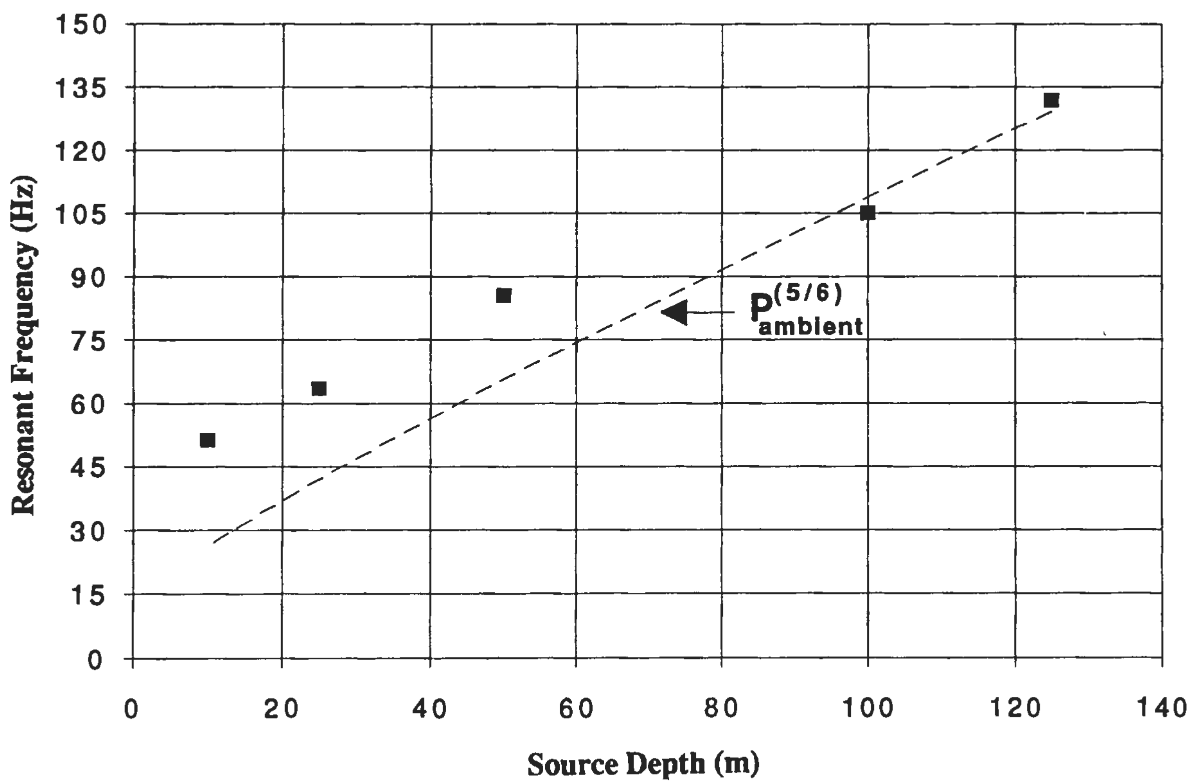


Figure 19. Depth dependence of 20-in^3 air gun resonant frequency based on reciprocal of initial bubble pulse period compared to prediction based on overburdening hydrostatic pressure [4].

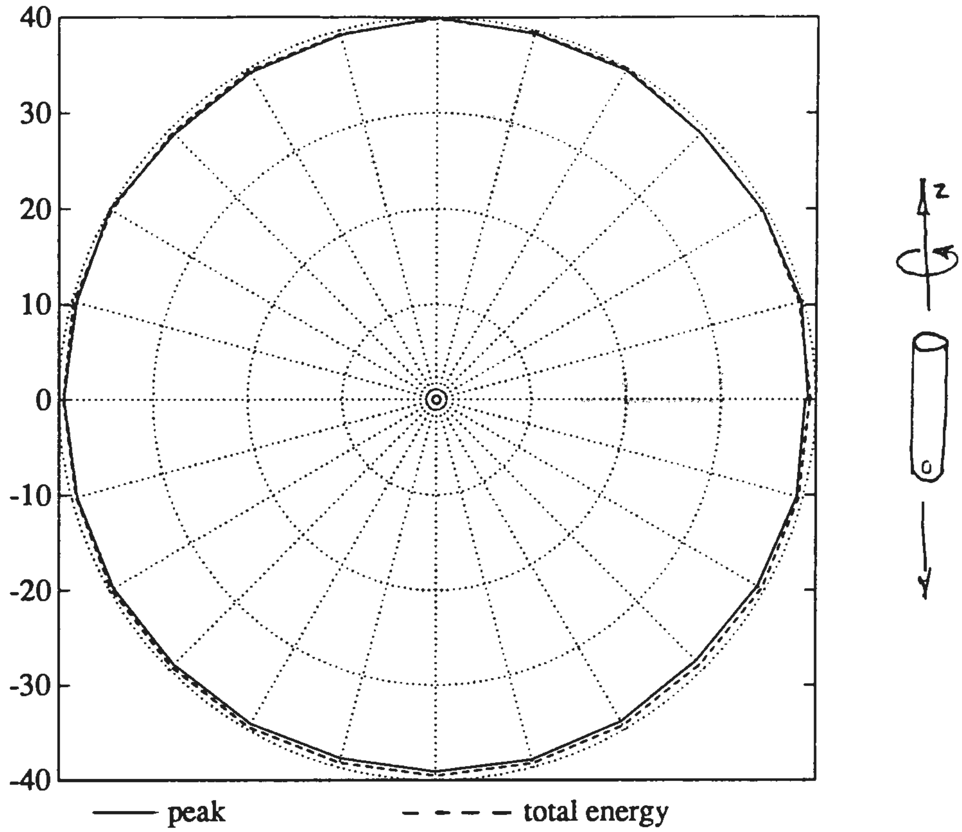


Figure 20a. 1-in^3 water gun longitudinal transmit beampattern based on peak and total energy.

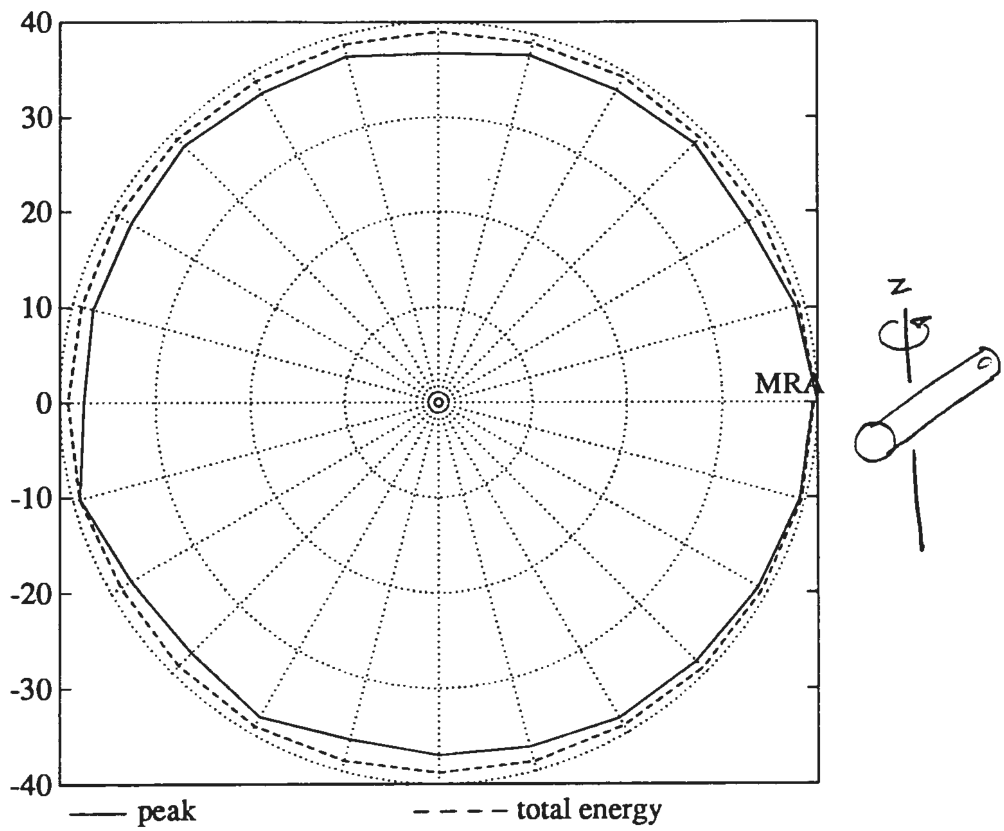


Figure 20b. 1-in^3 water gun azimuthal transmit beampattern based on peak and total energy.

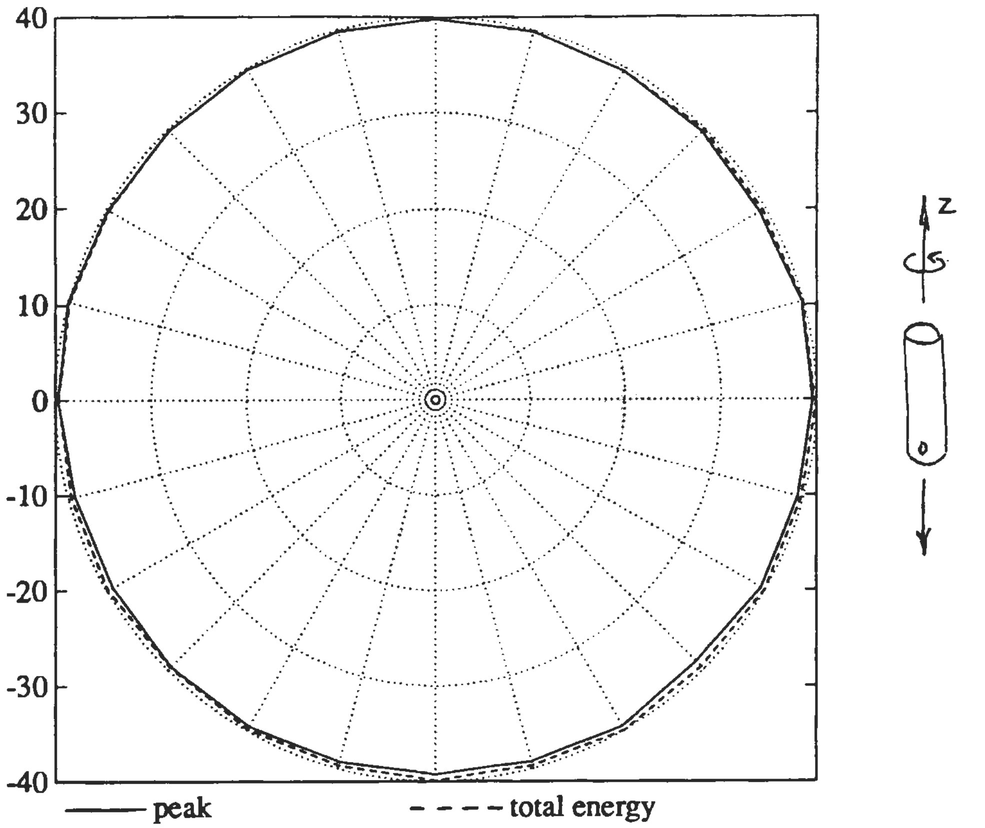


Figure 21a. 20-in^3 air gun longitudinal transmit beampattern based on peak and total energy.

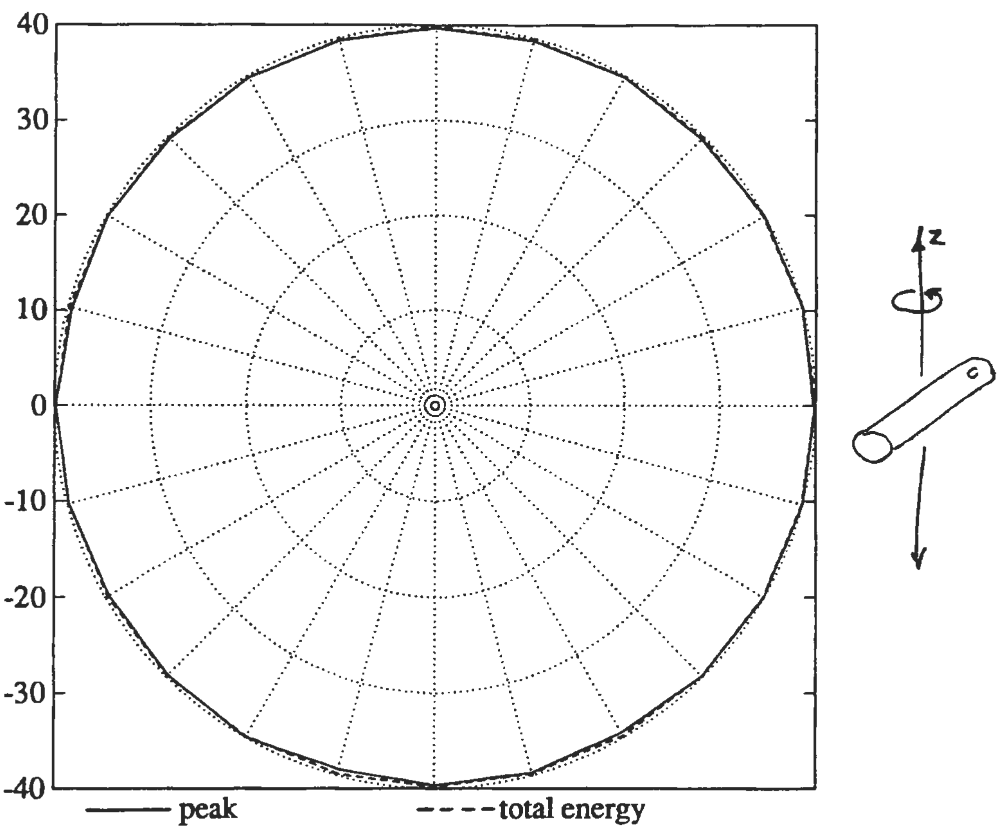


Figure 21b. 20-in^3 air gun azimuthal transmit beampattern based on peak and total energy.

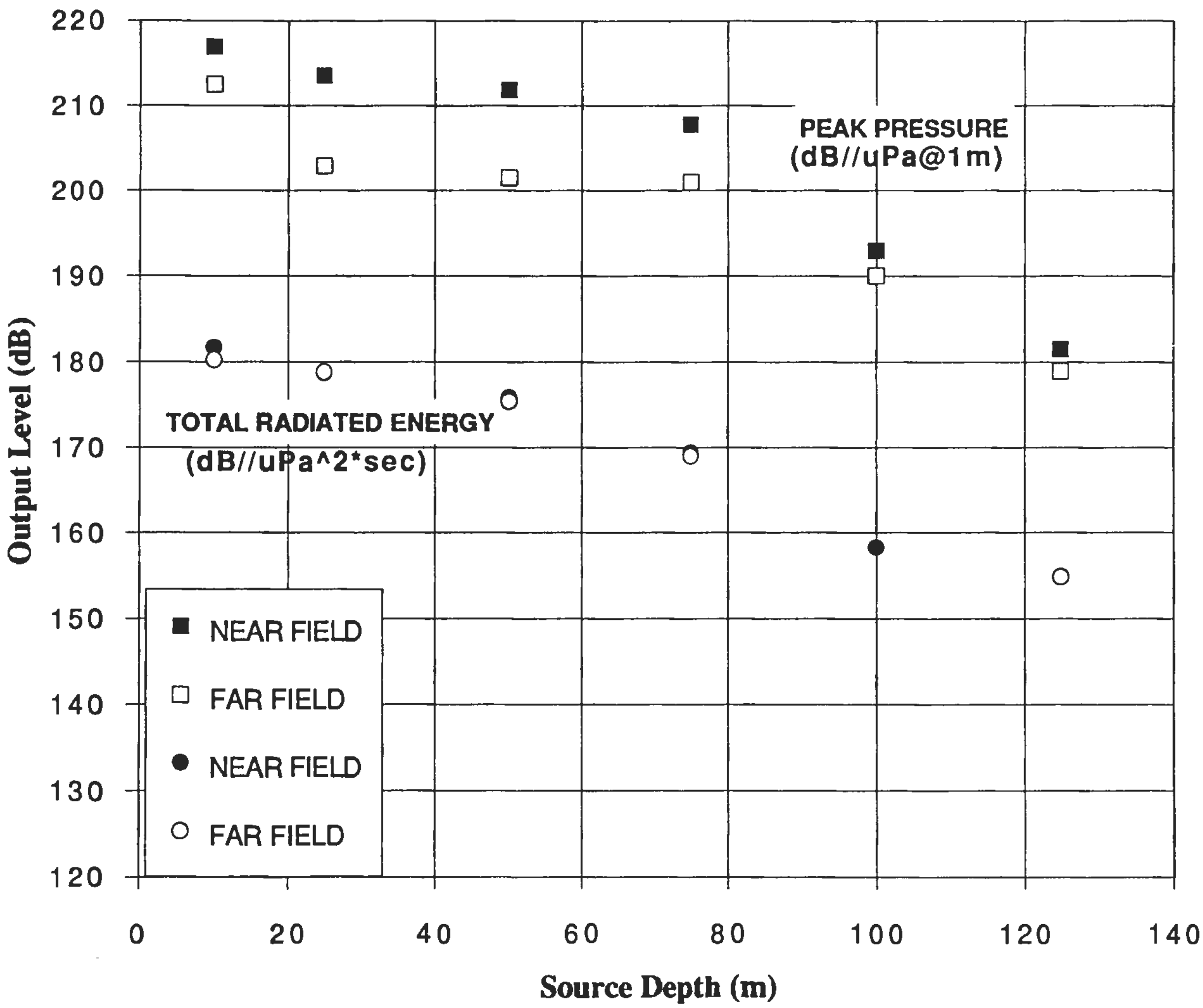


Figure 22. Depth dependence of output level for 1-in^3 water gun based on peak pressure and total radiated energy processing of near- and far-field acoustic energy.

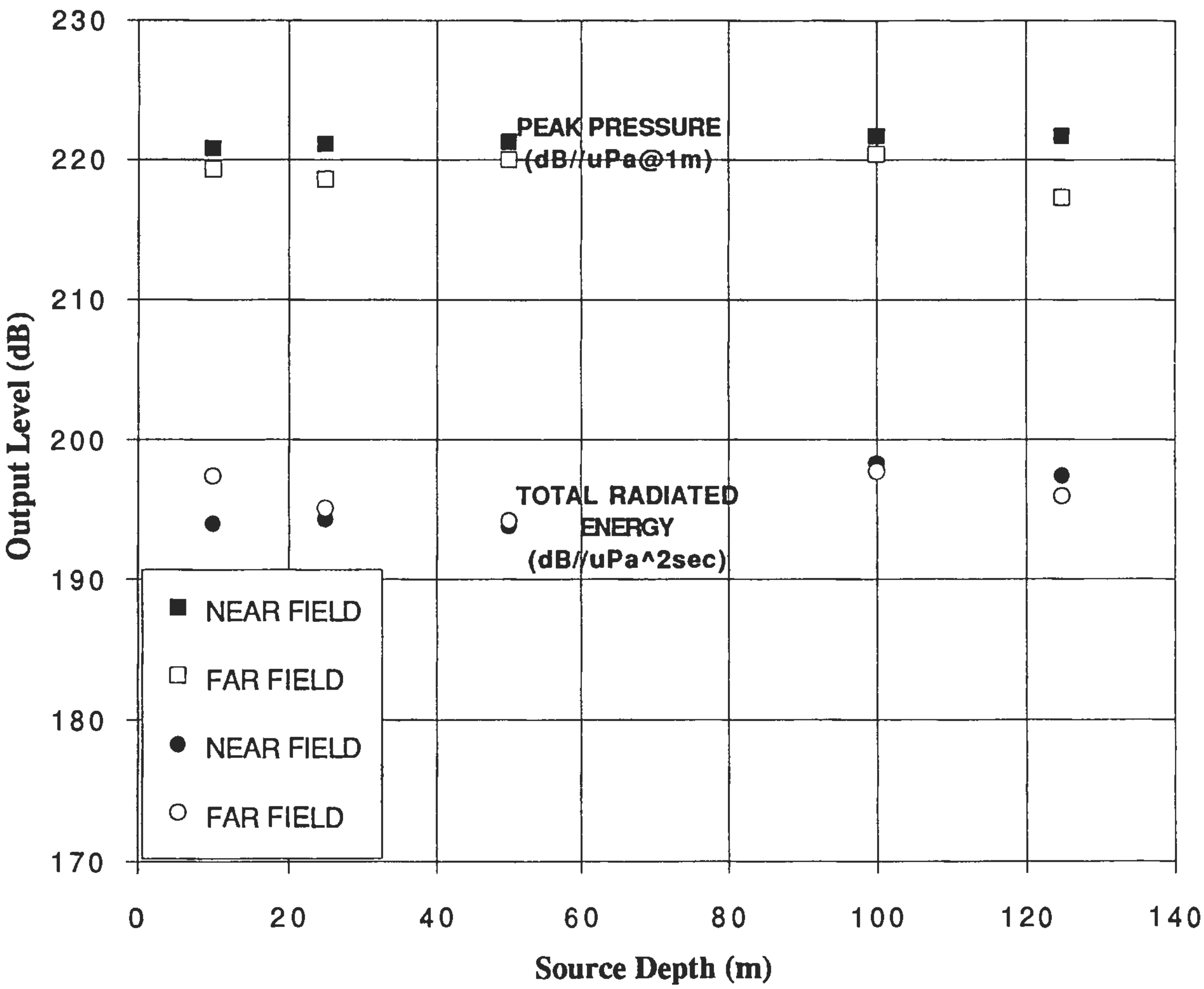


Figure 23. Depth dependence of Source level for 20-in^3 air gun based on peak pressure and total radiated energy processing of near- and far-field acoustic energy.

6.0 REFERENCES

1. J.H. Stockhausen and A. Figoli, "An Upward Looking Bistatic Research System for Measuring Deep Scattering Layers in the Ocean", SACLANTCEN TR 225, 15 May 1973.

2. Vaccaro, M.J., "Brief Given to the CST Volume Scatter Working Group, NRL-SSC", September 1992.

3. R.M. Noble and M.J. Vaccaro, "Test Plan for Seneca Lake POP Test (Water Gun Acoustic Source)", September 1992.

4. G. Parkes and L. Hatton, *The Marine Seismic Source*, (D. Reidel Publishing Company, Dordrecht, Holland), 1986.

5. M.H. Safar, "On the calibration of water gun pressure signature", *Geophysical Prospecting*, vol. 33, pp. 97-109, 1985.

INITIAL DISTRIBUTION LIST

Addressee	No. of Copies
External	
SPAWAR PMW 182-52 (Bohman)	1
NRL (Erskine)	1
ONR AEAS (Feden, Dial)	2
ONR/AEAS, Stennis (Small)	1
NRL-SSC (Love)	1
NAVOCEANO (O'Neill, Copling, Beeson, Jerret, Letourneau)	5
PSI/NL (Santaniello)	1
Bolt Technology Corp. (Chelminski)	3
Internal	
02151 (New London)	1
0261 (Library NL)	2
0262 (Library NPT)	2
10	1
31	1
311	1
3112 (Syck, Chester, Sundvik, Christian, Tattersall, Vaccaro (3))	8
3121 (Dullea)	1
3131 (Potter)	1
33A (Herstein, Monti, Malone, Koenigs)	4
332	1
3321 (Seaman, Noble (2))	3